COBALT

OCCURRENCE IN SOILS AND FORAGES IN RELATION TO A NUTRITIONAL DISORDER IN RUMINANTS

A REVIEW OF THE LITERATURE

AGRICULTURAL INFORMATION BULLETIN No. 7

UNITED STATES DEPARTMENT OF AGRICULTURE
Agricultural Research Administration
Washington, D. C.
March 1950

COBALT: Occurrence in Soils and Forages in Relation to a Nutritional Disorder in Ruminants—A Review of the Literature

By KENNETH C. BEESON, DIRECTOR, *U. S. Plant, Soil, and Nutrition Laboratory, Agricultural Research Administration*

CONTENTS

INTRODUCTION

Cobalt is the latest addition to the list of mineral elements known to be essential for the growth and health of ruminants. Its relationship to the health of other animals has not yet been established. Its role as an essential element became known through long-time studies of certain peculiar diseases of grazing animals (*159*)[1] having different names but similar symptoms in different areas, and now held to have common cause.

Among these disorders are "bush sickness" and "Morton Main disease" of New Zealand, "coast disease" of Australia, "salt sick" in Florida, "pining disease" of Scotland, "nakuritis" of Kenya Colony in Africa, an unnamed disease in Dartmoor, England, and "neck ail" of Massachusetts. Other reports include "Burton-ail" of New Hampshire (*94*), "Grand Traverse disease" of northern Michigan (*26*), and

[1] Italic numbers in parentheses refer to Literature Cited, p. 34.

ailments in Wisconsin (*77*), the Hebrides (*42*), and Norway (*66*). The occurrence of these nutritional disorders in the United States has been mapped by Beeson (*32*).

Animals having any of these diseases lose appetite and weight, become weak and anemic, and finally die. Long before anything definite was known about its cause each disease was recognized as being limited to certain areas of a country and prevention and cure were effected by transferring animals from "sick" to "healthy" areas.

The history of the investigations of these variously named ailments has been summarized by Marston et al. (*120*). Wunsch (*190*, *191*) discussed the extensive research in New Zealand, where investigation of the cause of "bush sickness" began about 45 years ago. From observations in "sick" and "healthy" areas and from the shifting of animals from one area to another came the hypotheses that either an excess or a deficiency of some mineral element in the soil, and thus in the forage, was involved. Soil and crop analyses and feeding and fertilizer experiments were carried out.

As a result of a series of studies of which the first publication was made in 1911, Aston came to the conclusion that the disease was due to iron deficiency. His studies are cited and summarized in an article published in 1924 (*24*). He reported that ferric ammonium citrate cured the ailment and prevented its onset. Later, Aston reported (*25*) that limonite from certain deposits was specific. These discoveries provided practical and effective means of preventing and curing the disease in the field. Further studies by Grimmett and Shorland (*83*) in the North Island of New Zealand and by Rigg and Askew (*152*, *153*) in the South Island, however, produced evidence against the explanation that the cures achieved were due to iron. It was postulated that some other inorganic constituent must be involved.

The importance of cobalt as a limiting factor in the nutrition of sheep and cattle in the United States has resulted in several investigations of its occurrence in the vegetation and soils in trouble areas. Much of the pertinent literature is found in foreign journals and is not readily available to those engaged in field work. Furthermore, the volume of the cobalt literature suggests the need for a summary and evaluation of those reports dealing with the cobalt content of vegetation and its relationship to soil. In this review the purpose has been to present a critical and comprehensive survey of the literature rather than a series of abstracts of individual papers.

DISCOVERY OF COBALT AS AN ESSENTIAL ELEMENT IN RUMINANT NUTRITION

In the meantime, experiments which eventually established cobalt as the deficiency element had been in progress in other areas. Discovery of the specific role of this element apparently was made independently by Filmer and Underwood, working on "enzootic marasmus" in West Australia, and Marston and Lines from their studies of "coast disease" in South Australia. In 1933, Filmer (*68*), described the malady to which he gave the name "enzootic marasmus," pointed out its similarity to "bush sickness," and produced evidence against the iron-deficiency theory. He expressed the view that the diseases were due to the lack of some mineral essential for iron metabolism and associated in nature with iron. Later, Filmer and Underwood (*69*) obtained an iron-free extract of limonite which was curative. Continuing their work, they reported in 1935 (*181*) that the limonite extract owed its potency to cobalt and described the cure of the disease in cattle and sheep by the administration of cobalt salts.

The term "coast sickness" was applied by the early settlers of South Australia to a disease of sheep pastured in the coastal areas. Active investigations of the ailment were initiated in 1929. Working on the hypothesis that either a deficiency or an excess of some mineral element was involved, various feeding experiments were carried out. The results led to the belief that a lack of some trace element was responsible for the malady. The investigators had noted that an anemia developed progressively in the course of the disease. They were familiar with the published reports of the remarkable effects of cobalt in causing polycythemia in rats. From these considerations and from certain geochemical evidence which had accumulated, they were led to test the effect of the administration of cobalt. Cures by the use of this element were reported in 1935 by Marston (*118*) and by Lines (*104*). These studies are reported in greater detail in a bulletin by Marston and coworkers (*120*).

Following the reports of the successful use of cobalt in Australia, Askew and Dixon (*16*) demonstrated that cobalt salts were effective in preventing "bush sickness" at Glenhope and the ailment at Morton Mains in the South Island of New Zealand. Wall (*186*) reported similar results from the North Island.

In a bulletin published in 1931, Becker, Neal, and Shealy (*30*) stated that in Florida "salt sick" was an old problem with cattle grazing on certain types of soils and that it was the greatest single cause of loss to the cattle industry of the State. They mentioned that the Florida Experiment Station had worked on the problem intermittently for over 50 years. They described symptoms as complete loss of appetite, emaciation, weakness, and pale mucous membranes. As a result of their own studies, these writers reported that the disease was a nutritional anemia, that the forage was lower in iron or in iron and copper than that of "healthy" areas, and that when affected cattle were given traces of iron and copper the condition was overcome except in the most advanced cases. A deficiency of these elements in the feeds, they stated, was the cause of "salt sick."

Following the success with cobalt in Australia and New Zealand, Neal and Ahmann (*132*) tested the effect of this element in an experiment with calves in Florida. The basal ration used consisted of hay from a "salt sick" area, shelled corn, skim-milk powder, cod-liver oil, whole milk, and salt. A failure of appetite and growth resulted on the basal ration alone. The trouble was aggravated by the use of an iron and copper supplement, but was cured by cobalt administration.

Patterson (*138*, *139*) studied the ailment in Dartmoor, England. He found that the cobalt content of the soil and pasture was higher in the "healthy" area than in the "sick" area, and that a mixture of cobalt, manganese, and zinc salts cured the disease.

Bowstead and Sackville (*44*) reported that in western Canada sheep maintained for a relatively long period on a dry ration of nonleguminous hays from certain regions, oats, and mineral supplements developed a cobalt deficiency.

Corner and Smith (*58*) reported striking benefits from cobalt administration to ewes suffering from "pine" in the Cheviot Hills, Scotland. They consider that the benefits previously ascribed to iron were probably due to cobalt, present as an impurity in the iron salts used. "Pining disease" has recently been described by Greig and coworkers (*81*).

Species Affected by Cobalt Deficiency

Cattle and sheep are the only species thus far known to be susceptible to cobalt deficiency. Cattle appear less susceptible than sheep in that they have frequently been reported unaffected in areas where the trouble is common in sheep. Filmer and Underwood (*70*) state that the disease runs a more rapid course in sheep and calves than in mature cattle. Horses have been reported unaffected in areas where sheep suffer from "enzootic marasmus," "bush sickness," and "pining disease." The "salt sick" of Florida has been reported in swine and goats as well as calves, but this term evidently covers ailments caused by more than one deficiency. No cures of goats and hogs by cobalt administration have been reported. Underwood and Elvehjem (*180*) were unable to produce evidence of cobalt deficiency in rats, but the diet they used was not low enough in the element to provide an intake per unit of body weight below that found curative for sheep. Thompson and Ellis (*178*) could find no evidence that additional cobalt was beneficial to a rabbit on a basal diet providing 1 microgram of cobalt a day.

Possible Role of Other Elements

The evidence is clear that there is no cure without cobalt for "coast disease," "enzootic marasmus," or "bush sickness." There is evidence, however, that certain other elements may be beneficial in some cases, indicating that deficiencies other than that of cobalt may exist in some areas.

In studies with mature sheep Marston and McDonald (*120*) found that treatment with iron and copper brought temporary improvement in some cases but failed to arrest the fatal course of the disease. Cobalt with copper or with copper and iron brought manifest improvement and restored most of the animals to normal health. With lambs (*120*) copper alone was ineffective, while cobalt alone permitted growth in some animals but did not prevent the progressive development of anemia. Copper plus cobalt caused satisfactory growth, cured mildly affected animals, and prevented the development of anemia. These authors suggest that a dual deficiency of copper and cobalt in affected areas causes "coast disease."

Lines (*120*) found that in one area on Kangaroo Island sick ewes did not respond to cobalt but did to cobalt plus copper; that in another area they did not respond to cobalt alone but did to a mixture of cobalt, iron, zinc, and manganese.

Nickel has been tested frequently. Evidently the nicket salt used in studies before the essential role of cobalt was discovered contained cobalt also. Dixon (*62*) fed one group of lambs 0.8 mg. of nickel-free cobalt weekly and another group cobalt plus 0.16 mg. of nickel. The second group made better gains. The results are considered statistically significant.

Filmer and Underwood (*71*) expressed the view, based on their experiments, that traces of nickel increase the action of suboptimum levels of cobalt. They found that although 0.3 to 1 mg. of cobalt daily was an adequate supplement for cattle for 12 months, the gains made on the suboptimum intake of 0.05 mg. were improved by the addition of 0.02 mg. of nickel. The differences were significant statistically. Von Zeppelin and Glass (*195*), in studies of "enzootic marasmus" in sheep, claim benefits from nickel, particularly as a supplement to cobalt.

Pathology of Cobalt Deficiency

The commonly reported physical symptoms of cobalt deficiency, in both growing and mature animals, are listlessness, dullness, and, frequently, watering of the eyes, unhealthy coat, loss of appetite, slow growth or loss of weight, general weakness, and bleaching of the mucous membranes. The animal wastes away and finally dies. Clearly, this is a general rather than a specific picture of malnutrition, giving no precise information on the role of cobalt. Wool growth is markedly affected in sheep (*154*). Cows are difficult to breed, abortions may occur, and lactation is depressed. These effects are to be expected in general malnutrition, and thus cannot be considered as specific or direct effects of a cobalt deficiency.

Cobalt Requirements

A surprisingly small quantity of cobalt is required to prevent or cure the disorders which respond to its administration. The quantities reported in the literature are those that have been found effective as supplements to forage grown in "sick" areas. Thus they are not absolute values as the forage itself was not devoid of cobalt. The data have been obtained both by feeding cobalt salts and by feeding soil or mineral extracts the cobalt content of which was estimated. Obviously the second method is less reliable than the first, because elements other than cobalt were fed and also because the chemical determinations may have been inexact.

Most of the values reported were obtained with sheep. In the "coast disease" area, sheep in an advanced stage of the disease responded in appetite and in general condition to daily administrations of 1 mg. of cobalt as cobaltous nitrate (Lines, *104*, *120*). No work at a lower level was reported.

Studies of "enzootic marasmus" (*70*, *71*, *181*) show that as small a daily intake of cobalt as 0.1 mg. is sufficient to cure the disease in sheep. This level was effective for optimum growth over a period of 14 months. Levels of 0.03 and 0.05 mg. gave a response but were too low for satisfactory growth.

For the cure of "bush sickness" in sheep in the South Island of New Zealand, Askew and Dixon (*16*) reported that feeding 8 mg. of cobalt a week was successful. The growth was double that of the controls, the blood picture was normal, and wool growth was markedly better. Later these workers (*18*) reported that the minimum intake necessary for health is 0.6 mg. a week.

If 0.1 mg. a day for sheep is accepted as the minimum addition to cobalt-deficient forage, the total requirement may be estimated by considering also the quantities which have been found in the forage. From a review of New Zealand studies, Wunsch (*191*) states that an average of 77 "sick" pastures contained 0.038 p. p. m. of cobalt in the dry matter. Underwood and Harvey (*182*) reported an almost identical figure—0.04 p. p. m.—for "sick" areas in Australia. Assuming that a 100-pound lamb eats 2.5 pounds of dry matter daily, pasture containing 0.04 p. p. m. would supply approximately 0.045 mg. daily. Adding this to 0.1 mg. would give a daily requirement of about 0.15 mg.

Indirect evidence on a cobalt requirement which should be adequate is obtained by considering its content in the forage of "healthy" areas. Wunsch (*190*) summarized the data from the New Zealand studies as follows:

Cobalt in forage:		*Effect on livestock*
0.01 p. p. m. dry weight		Serious sickness in sheep and cattle.
0.04	do.	Serious sickness in sheep; some in cattle.
0.04–0.07	do.	Some sickness in sheep; cattle fairly healthy.
0.07–0.3	do.	Sheep and cattle healthy.

Wunsch reports the average value of 0.106 p. p. m. for 39 "healthy" pastures. Underwood and Harvey (*182*) report an average value of 0.13 p. p. m. for "healthy" areas adjacent to a "sick" area, and a value of 0.18 p. p. m. for "healthy" areas outside the "sick" district. Taking the lower value reported by Wunsch and assuming that a 100-pound lamb eats 2.5 pounds of dry matter a day, the intake would be computed as 0.12 mg. a day. Similarly, 0.13 p. p. m. in the forage would provide an intake of 0.15 mg. a day.

For the cure of "enzootic marasmus" in cattle, Filmer and Underwood (*70*) found 0.3 to 1.0 mg. effective. This indicates a lower requirement per unit of body weight by cattle than by sheep—a finding that is borne out by observations in the "sick" areas that cattle appear to be less susceptible than sheep. On the other hand, in limited experiments by Neal and Ahmann (*132*) with calves fed hay from a "salt sick" area, 10 mg. daily gave better results than 5 mg. with one calf. A deficiency of some other trace element may have been involved and this element may have been present as an impurity in the cobalt salt used.

The cobalt requirements so far discussed here are those that have been found effective as preventives or cures as measured by appetite, growth, and general condition. No specific studies of the requirements for reproduction and lactation have been made. Reproduction failures and decreased lactation are commonly observed in the "sick" areas, but there is no specific evidence as to whether the requirements are greater during these periods. Marston (*120*) states that nutritional disorders are more severe during the strain of reproduction and lactation. According to Filmer and Underwood (*70*), wasting in cows is particularly rapid after calving or abortion.

COBALT CONTENT OF ROCKS AND OTHER SOIL PARENT MATERIALS

The availability of soil cobalt to a plant depends on many factors. The quantity of cobalt and its distribution throughout the soil profile, which are of primary importance, have received very limited attention. Other factors—the nature of the compounds of the element and the effects of moisture and other soil characteristics and of climate—are not well understood. The soil parent material is a factor of recognized importance as the original source of any mineral element, and some studies in relation to cobalt have been reported.

Cobalt cannot be classed as one of the more abundant elements of the lithosphere, but its general occurrence is indicated by its presence in practically all soils and vegetative tissue that have been examined for it. Clarke and Washington (*55*) state that the element is widely distributed, although in very small quantities, in igneous rocks that constitute about 95 percent of the lithosphere. Its relative rarity, however, is emphasized by Washington's estimate (*188*) that there is less than 0.23 percent of cobalt in the whole earth. Goldschmidt (*78*) suggests that a large part of the cobalt of the earth, because of partition between metallic or semimetallic phases and silicate phases, has been eliminated from the earth's crust. He believes therefore that the cobalt content of the crust does not exceed 40 grams per ton, or approximately 45 p. p. m. The difficulty of determining such small quantities of the element limited the number of cobalt analyses in rocks and soils until the necessity for studying its occurrence stimulated the development of relatively simple and accurate methods for its determination.

Recent work has emphasized that cobalt is not uniformly distributed in rocks and that its presence in any particular rock is not necessarily fortuitous but is based on physical laws. Clarke and Washington (*56*) recognized that cobalt would ordinarily be found in certain minerals, such as olivine and pyroxene. Tröger (*179*) stated in 1935 that a possible content of cobalt in eruptive rocks in most cases can be neglected, and that only in the unusually rich sulfide rocks is more than 0.01 percent of it found. Much smaller quantities, of course, are exceedingly important in relation to the supply of this element for animals.

The first fundamental study on the distribution of cobalt was that reported by Goldschmidt (*78*) in 1937. He utilized the principle of partition of elements between a metallic liquid, a semimetallic sulfide (liquid phase), and a silicate (liquid phase) as a means of accounting for the low cobalt content of the earth's crust. A fourth group includes the elements which are accumulated in gaseous phases. According to Goldschmidt, the classification of distribution of cobalt would be as follows:

Iron, siderophile	Relatively high concentration.
Sulfide, chalcophile	Moderate concentration.
Silicate, lithophile	Low concentration.
Gases, atmophile	None.

Goldschmidt reasoned that the partition of elements in these groups is closely related to the structure of the electron shells of the atoms. Ions such as those of sodium, calcium, and aluminum enter preferentially into the ionic phases of silicate shell; the metallic elements of the transition group such as nickel, palladium, platinum, and cobalt enter preferentially into the iron alloys; and elements of the 18 electron shells, such as copper and lead into sulfide, melt if their oxidation-reduction potentials are not high enough to permit formation of their iron alloys. Thus, the greater part of the original cobalt con-

871666—50——2

tent of the earth was concentrated in the iron core and only negligible quantities were left in the great mass of silicate rocks.

A further sorting of cobalt is postulated by Goldschmidt. He points out that the formation of crystalline minerals involves the building up of space lattices of atoms or ions in a regular arrangement, depending upon the size or radii of the individual atoms or ions. Into such a lattice only particles of a size appropriate to the lattice spacings can enter. Cobalt, with a radius of 0.83 A., is closely associated with lithium, magnesium, nickel, iron, zinc, and tin. In the pair magnesium-nickel, the radii are the same—0.78 A.—as are also the charges of the ions. Being bivalent, both metals will enter into the silicate crystals of each other with about the same probability. Consequently, Goldschmidt states, the quantity of nickel in a number of magmatic minerals is roughly proportional to that of magnesium. If radii, charges, and the ionic type of two elements are exactly alike or very similar, no separation takes place. If, however, there is some small difference of ionic radius, the bond is weakened for the larger ion. Thus:

Forsterite, Mg_2SiO_2, m. pt. 1910° C.
Fayalite, Fe_2SiO_4, m. pt. 1205° C.

Ions of different charge enter a crystal structure in the order of their electrostatic charge, as long as simple atomic ions are involved. The ion having a larger charge has the preference over other ions of the same size but of lower charge. Thus:

Anorthite, $Ca^{++}(Al_2Si_2O_8)$ = m. pt. 1550° C.
Albite, Na^{+} $(AlSi_3O_8)$ − m. pt. 1090° C.

Goldschmidt found that calcium is concentrated in the first fractions of plagioclase crystals and sodium is present in the later fractions.

The importance of this principle in relation to cobalt is suggested by the work of Wager and Mitchell (*184*, *185*) on the Skaergaard intrusion of Kangerdlugssuak, Greenland. This comprises a series of gabbros and related rocks which has been interpreted as the result of fractional crystallization of a fairly normal gabbro magma. Thus, according to Wager and Mitchell, the rocks consist of a precipitate of all the solid phases separating at a particular time from the magma, with about 20 percent of a magma then existing. In this series the normal gabbro, an olivine, contains about 75 p. p. m. of cobalt. A gabbro-picrite, the first in the series of separates, contains 100 p. p. m. of cobalt; an acid, granophyre, the last to crystallize out, contains about 4 p. p. m. Wager and Mitchell (*184*) conclude that no deficiencies in cobalt would be expected in soils derived from ultrabasic rocks, and the extensive studies of Nockolds and Mitchell (*135*) contribute further proof of this characteristic distribution of cobalt.

Lundegardh (*106*) reported a similar distribution of cobalt from intrusive rock in an eastern upland in Sweden. In the normal differentiate, he found this element distributed as follows: In pyroxenite-hornblendite, 40 p. p. m.; in basic quartz-gabbro, 40 p. p. m.; in diorite, 48 p. p. m.; in late diorite, 25 p. p. m.; in granite, 11 p. p. m.

He reported an even more striking distribution in the late normal differentiate. In the order of crystallization, the cobalt content was as follows: In peridotite, 200 p. p. m.; in allivalite, 60 p. p. m.; in ultrabasic norite, 65 p. p. m.; in amphibole-gabbro, 23 p. p. m.; in microcline granite, 0.5 p. p. m.

Further evidence has been offered by Lundegardh (*105*), who found that olivine, consisting of 20 percent Fe_2SiO_4 and containing large quantities of magnesium, had a cobalt content of 250 p. p. m. Clinopyroxene from the same intrusion (30 to 35 percent $FeSiO_3$ and with still more magnesium than iron) contained 130 p. p. m. of cobalt. However, titano-magnetite (99 percent $Fe_2(FeTi)O_4$ and containing very little magnesium) had a cobalt content of only 50 p. p. m. Thus, the higher the magnesium content, the lower the iron and the higher the cobalt content.

Sandell and Goldich (*161*) examined a number of American igneous rocks and found cobalt to be relatively low—0.5 to 5.0 p. p. m. in the granites, as compared with 26 to 45 p. p. m. in the diabases. Apparently these rocks did not come from the same differentiates, but the cobalt levels suggest trends similar to those found by Lundegardh and by Wager and Mitchell. Bray (*45*), working with Colorado rocks, found that cobalt was highest where biotite and hornblende were abundant. He suggests that it occurs as a substitute for magnesium and iron.

Carroll (*51*, *52*) suggested these relationships with respect to the problem of cobalt deficiencies in Australia. She observed two conditions that seem to influence the cobalt content of the soil: (1) The character of the ferromagnesium compounds in the parent rock may vary widely in their minor element content, depending on their origin; (2) the rate of weathering may govern the supply of these elements. In Australia, fresh unmetamorphosed intrusions of dolerite, which contain augite and feldspars in abundance and weather readily, are associated with healthy animals. Igneous intrusions of gneisses that weather slowly and contain ferromagnesium of a different minor element content are associated with cobalt deficiency. Carroll assumes that ferromagnesium crystallized from a magma can differ materially from one crystallized from a gneiss and the theoretical requirements discussed above seem to support this assumption. Thomas (*177*) found that Australian soils derived from sedimentary rocks such as the sandstones are deficient in the heavy metals in the proportion that the rock is lacking in minerals rich in them.

Data from several investigators (*13*, *63*, *117*, *122*, *151*, *170*) indicate a low level of cobalt in limestones. The over-all range is 0.2 to 12.5 p. p. m. of cobalt, with many values falling between 1.0 and 5.0 p. p. m. Stanton (*170*) found no correlation between the geological age and the cobalt content of a number of limestones. Maunsell (*122*) reported that limestones of different ages did fall into certain groups with respect to cobalt content, but probably the presence of ultrabasic rocks in the neighborhood had more influence on the cobalt content than did age. Residual soils from limestones have up to a hundred times as much cobalt as does the virgin rock (*63*, *151*, *170*). McNaught (*112*) reported, on the basis of an extensive study of limonites of New Zealand, a cobalt range of 1.0 to 363 p. p. m. Several of these had been used in the treatment of cobalt deficiency in cattle.

COBALT CONTENT OF SOILS

It is frequently stated that Luynes in France was the first to detect cobalt in the soil. A report by Brongniart in 1836 (*48*), however, shows that he found cobalt in a black sandstone vein far beneath the actual soil. Concentration of cobalt in such a vein probably made its detection much easier than it would have been in the soil itself. Forchhammer (*72*) probably found cobalt in soils as early as 1855. Robinson (*155*) in 1914 published a number of determinations of nickel plus cobalt in some soils of the United States.

Bertrand and Mokragnatz seem to have been the first to have definitely determined cobalt alone in soils. Their work indicates that cobalt must be widely distributed, regardless of the kind or origin of the soil. In 1922 they reported (*37*) finding 28 p. p. m. of cobalt in a very fertile soil from Pantchevo (near Belgrade), Yugoslavia, and 37 p. p. m. of cobalt in a garden soil at the Pasteur Institute in France. Bertrand and Mokragnatz reported on more extensive surveys in 1924 (*39*) in which they had collected and examined soils from many places in France, Denmark, Italy, Germany, and Rumania. Although their samples were taken in 20 localities and from about 15 geological formations, including volcanic terrain in Italy, the range in cobalt content of the soils examined is narrow. The values reported vary from 0.3 p. p. m., in the air-dry soil, to 11.7 p. p. m., and the distribution of values is very regular—that is, no one class predominates. McHargue (*110*) reported in 1925 that he had found 1.5 p. p. m. of cobalt in a hydrochloric acid extract of a virgin soil in Kentucky.

Distribution of Cobalt in Soil Profile

There is some evidence of a definite distribution of cobalt throughout the mature soil profile. Bertrand and Mokragnatz (*39*), for example, found an accumulation of cobalt in the surface horizons of several soils and a leaching effect in the middle horizons (table 1). The differences are small, however, and their significance is not certain.

TABLE 1.—*Cobalt content of soil horizons in France* [1]

Locality	Soil horizon	Geological formation	Cobalt in air-dry soil
	Cm.		*P. p. m.*
Sainte-Chaptes	0–20	Oligocene	4.6
	20–40	do	4.1
	40–60	do	5.5
Aubord	0–20	Recent alluvium	4.7
	20–40	do	4.1
	40–60	do	5.2
Genolhac	0–20	Disintegrated granites	2.4
	20–40	do	2.2
	40–60	do	3.8

[1] From Bertrand and Mokragnatz (*39*).

An accumulation of cobalt in the upper horizons of the soil is quite possible, as a result of normal soil-building processes. In fact, there is some evidence of such accumulations. In 1906, Kraut (*101*) reported the presence of cobalt in the ash of peats from Tannenhausen, Haidlinger, and Papenburg and of lignites from Bitterfeld and Ihringshausen in Germany. Goldschmidt (*78*) reported large accumulations of cobalt in the ashes of coal. Thus, although he estimates a content of only 40 grams of cobalt per ton of the earth's crust, he found 1,500 grams of cobalt per ton of coal ash. He postulates that the insoluble compounds, such as those of cobalt, absorbed by vegetation and subsequently returned to the soil in dead vegetative tissue are filtered off in the humus layer of the soil. An adsorption of this element by the organic colloids might also offer an explanation for its accumulation.

The data of Slater, Holmes, and Byers (*166*) also show that one or more of the upper horizons of several soil profiles have higher cobalt contents than do the lower horizons. The largest accumulation is not always in the first horizon (table 2), and some profiles, such as the Palouse silt loam and the Nacogdoches fine sandy loam, have a distribution of cobalt somewhat similar to that of iron as a result of the podzolization process. The distribution of cobalt in the two profiles cited agrees in general with that in the soils examined by Bertrand (table 1). The quantities of cobalt reported by Bertrand, however, are somewhat higher than those reported by Slater, Holmes, and Byers.[2]

TABLE 2.—*Cobalt content of soil horizons in the United States* [1]

[In parts per million]

Soil type	Great soil group	Parent material	Cobalt in horizon—					
			1	2	3	4	5	6
Clinton silt loam	Gray-brown podzolic.	Loessial	1.1	----	1.6	1.7	1.6	----
Colby silty clay loam.	Chernozem	do	.2	0.2	.2	.1	.1	0.2
Marshall silt loam.	Prairie	do	1.9	2.4	.9	.9	----	----
Palouse silt loam	Chernozem-prairie.	do	.6	0	1.7	1.9	1.8	----
Shelby silt loam	Prairie	do	.4	.6	1.0	1.4	.1	.2
Nacogdoches fine sandy loam.	Lateritic	Limestone	.9	.3	.4	.2	.2	----
Houston black clay.	Rendzina	do	1.4	1.4	.9	.9	----	----
Muskingum silt loam.	Gray-brown podzolic.	Shale	.2	.4	.1	.1	.1	----
Kirvin fine sandy loam.	Lateritic	Heavy clays	1.0	1.0	.9	.9	.6	----

[1] From Slater, Holmes, and Byers (*166*).

EFFECT OF SOIL PARENT MATERIAL ON NUTRITIONAL DISORDERS IN ANIMALS

Sound theoretical reasons for the abundance or scarcity of cobalt in certain kinds of rock have been advanced. There is additional evidence that the distribution of cobalt follows a sufficiently definite

[2] Slater et al. determined the cobalt soluble in hydrobromic acid and assumed that this reagent would dissolve that portion of the total cobalt in the soil available to the plant. It is not known if the hydrobromic acid soluble is equivalent to the total cobalt.

pattern to permit certain assumptions as to the abundance or scarcity of this element in soils. The most thorough work has been done in New Zealand and Australia, although some reports have come from England, Scotland, and the United States.

Grange, Taylor, Rigg, and Hodgson (*79*) surveyed trouble regions in North Island, New Zealand, in 1932, before cobalt was known to be the limiting element. The Taupo shower is typical of the many deficient soils of volcanic origin there. It consists of fragments of rhyolitic pumice, obsidian, banded flow rhyolite, shreds of glass, and grains of quartz, feldspar, hypersthene, and magnetite. It is high in silicon, sodium, and potassium and relatively low in iron, magnesium, calcium, titanium, manganese, and phosphorus. Kidson (*96*) later found the soils in this area to be very low in cobalt (table 3). The low contents of magnesium and iron are significant in view of the association of these elements with cobalt. Ash deposits in the deficient area were mainly rhyolitic in composition, whereas the showers associated with healthy animals contained andesite, which probably accounts for the differences in the quantities of magnesium in the soil. Clarke (*54*) reported the presence of nickel in andesite, which is significant in view of the known associations of nickel and cobalt. Kidson (*97*) found more cobalt in soils developed from andesite than in those from either granite or rhyolite.

Grange also observed that farms in the deficient area were generally on lowland and upland flats or easy slopes and occasionally on moderate slopes. Wherever the slope was steep enough to prevent accumulation of the shower the land was suitable for pasturing stock.

Volcanic showers are not the only geological formation associated with the incidence of cattle disease in New Zealand; it has long been known that some of the granite country also is unsound. Askew and Rigg (*21*) and Rigg (*151*) reported that granite soils associated with "stock-ailment" (now identified as a cobalt deficiency) occurred for the most part in hilly regions and frequently in steep ones. River flats derived from granite wash, however, were just as much affected as the hill country. Two other soil types in this locality developed on a different material are sound with respect to animal disease, although one of them, the Montere Hills type, is not a fertile soil. This soil was developed from "much-weathered gravel deposits, consisting largely of claystone, sandstone, and grey-wacke."

Other observations in this area indicate that pastures on loessial soils are much lower in cobalt than are those on alluvial soils, but no adequate description of the character of these materials has been presented. Askew (*9*) noted in the Nelson district of New Zealand that soils developed on granites were associated with cobalt deficiency in sheep. Wherever Miocene strata in addition to granite are encountered, the soils are better. On some farms the Miocene strata are overlaid by a granite wash, which presents the same difficulties in connection with sheep as do the granite soils. Further work in this area by Stanton and Kidson (*171*) confirmed these observations. On soils from limestones, basic rocks, and slates, and of alluvial material, animals were generally free from the nutritional disorder.

Patterson (*140*) reported a cobalt deficiency in soils derived from granite and certain sandstones in Devon and Cornwall. Those derived from Middle Devonian shales were good, however. Beeson,

TABLE 3.—*Cobalt content of some New Zealand soils (cobalt extracted by concentrated HCl)*[1]

Soils associated with cobalt deficiency			"Good" soils		
District and description	Cobalt content		District and description	Cobalt content	
	Average	Range		Average	Range
Central North Island Volcanic:	*P. p. m.*	*P. p. m.*	Central North Island Volcanic:	*P. p. m.*	*P. p. m.*
Kaharoa ash shower	0.9	0.8–0.9	Tarawera ash shower, a recent shower covering some of the Kaharoa areas.	5.4	4.3– 7.0
Taupo ash shower, sub-aerial deposition	1.4	1.0–1.8	Hamilton ash shower	16.8	12.5–22.5
Taupo ash shower, water-sorted soils	1.2	1.0–1.4	Alluvial soils derived in great part from volcanic ash.	5.3	2.5– 9.5
Tarawera ash on Kaharoa, but disturbed by plowing.	2.5		Ngauruhoe ash shower	3.0	
			Resorted Kaharoa ash	2.8	
Waimea County, Nelson:			Waimea County, Nelson:		
Kaiteriteri sandy loam, Glenhope	0.4		Waimea stony loam	25.5	
Sherry loam	1.2	0.7–1.8	Waimea clay loam	17.5	17.0–18.0
			Waimea loam	15.2	8.5–19.0
			Various loams	25.4	2.5–85.0
Collingwood County, Nelson	2.0	0.5–3.5	Collingwood County, Nelson	2.2	1.5– 3.0
Morton Mains	4.0	3.3–4.8	Morton Mains	5.5	2.8–8.3

[1] From Kidson (*96*).

Gray, and Smith (*35*) showed that cobalt deficiency in the White Mountains of New Hampshire and on Cape Cod is associated with granite soils in both areas. Lyford, Percival, Keener, and Morrow (*108*) found that most of the cobalt deficiency cases in New Hampshire occurred on soils developed from granites.

Thomas (*176*) has recently published a careful description of the "healthy" and "affected" soils on Kangaroo Island and in Robe District, South Australia. Most of the ironstone or ferruginous clay soils on Kangaroo Island not associated with animal ailments are derived from ancient pre-Cambrian metamorphic rocks. In many places the original character of these ferruginous soils has been altered through the transport of clay and fine silt fractions to the lower valley levels, leaving on the uplands a poorer soil consisting essentially of quartz sands and ferruginous "laterite." Thomas observes, however, that although the soils derived from the pre-Cambrian rocks may differ in fertility from place to place, they are invariably satisfactory as far as cobalt deficiency is concerned.

The geological formations in South Australia which tend to be associated with cobalt-deficient soils, according to Thomas, are restricted to calcareous dune sands in various stages of consolidation and lacustrine limestones, which are often derived from the same source. These dune sands consist almost entirely of comminuted marine shell fragments, which, with a little quartz sand, have been blown inland by the prevailing winds. The older dunes become fixed by vegetation and eventually are consolidated by solution and redeposition of the calcium carbonate.

Thomas states that where the dune sands have become consolidated, there is a tendency for the calcium carbonate to be leached downward and to leave a surface layer of quartz sand, with such small amounts of argillaceous material as were originally present in the dune sand. The continued addition of decayed vegetable matter to this surface layer results in a poor class of light sandy soil. Poor as such soils undoubtedly are, it is believed that they could be profitably cleared for sheep grazing were it not for the fact that cobalt deficiency is so pronounced. Their relatively high carrying and fattening capacity, especially in early spring, has been repeatedly demonstrated.

Soils derived from lacustrine limestones and marls in trouble areas are naturally somewhat more loamy or argillaceous, according to Thomas. While admittedly poor in plant nutrients, they respond remarkably well after clearing and top dressing, although they remain deficient in cobalt. Thomas differentiates between these limestone soils, which contain up to 80 percent limestone, and the fertile residual soils formed from limestone, which normally contain very little calcium carbonate, if any. Riceman, Donald, and Piper (*148*) reported in 1938 that vegetation on these calcareous dune sands responded remarkably to applications of copper sulfate, but they made no observations as to any effect on the health of sheep grazing the pastures. The recent work of Crocker (*60*) confirms these studies on calcareous dune sand soils.

Coastal soils high in calcium derived from shell fragments are reported (*80*) to be associated with a disease of sheep and young cattle called "pine" on Tiree Island, Scotland. McNaught and Paul (*117*) noted a cobalt deficiency on a limestone soil in New Zealand. The soil had been built up as a fan formation by redeposition of fine limestone particles. McDonald (*109*) also observed cobalt deficiency in relation to what he termed a "lime-humus" soil—a layer of black friable clay of variable depth and stoniness overlying limestone. The soil was normally flooded during the wetter months.

Coastal areas or coastal plain areas of recent origin have been associated with cobalt deficiency. Often deficiencies of other mineral elements, such as copper, complicate the picture. Ender (*66*) observed their frequent occurrence on sandy soils along the rainy coastal regions of Norway. Although copper deficiency is suspected in this district, that of cobalt is believed to be more critical. Boddie (*42*) mapped several areas of cobalt deficiency in the sandy soils of the Hebrides. Where the soils were relatively high in organic matter, less trouble was observed. A number of coastal plain soils in Florida have been classified according to their cobalt deficiency (*28*, *29*, *30*). In general, the sands and fine sands have a much lower cobalt content and are more often associated with nutritional deficiencies in animals than are the sandy loams. The good soils contain over twice as much silt and clay in the first foot and over three times as much in the second foot as do those soils in the "salt sick" area (*49*). The trouble occurred on both calcareous and low-lime soils.

All Florida soils have developed under rainfall which fluctuates between 30 and 80 inches, averaging about 50 inches. Both the "salt sick" and normal soils are notably deficient in plant nutrients and cobalt (*28*), and careful management is required for normal yields of any crop. It would seem that the Florida soils bear little relationship to either the volcanic showers of New Zealand or the calcareous dune sands of Australia, except that some of the Florida soils, like the dune sands, are of marine origin. They are for the most part, however, very acid, whether they are developed from calcareous formations or from other materials. Most of the better soils are residual limestone soils.

Cobalt Content of Soils Associated With Cobalt Deficiency in Animals

Kidson reported in 1937 (*96*) on the cobalt soluble in concentrated hydrochloric acid in a large number of New Zealand soils both free of and associated with cobalt deficiency. Her data cover the topsoil only, often the upper 3 inches and seldom to a depth exceeding 6 inches. In view of the variations in the cobalt content of different horizons in the profile reported by other investigators, it is doubtful whether the cobalt in the surface layer of the soil is always a reliable indication of the cobalt content of the soil within reach of plant roots. Nevertheless, with a few exceptions, Kidson's data show that soils associated with animal ailments have comparatively low cobalt contents.

Kidson's data (table 3) indicate that the Kaharoa ash soils, the Taupo ash soils, the Kaiteriteri sandy loam in Glenhope, and the Sherry loams all have cobalt contents below 2 p. p. m. Soils such as the Morton Mains soils are much higher in cobalt than are some reputedly good soils. In fact, the cobalt range of the good Morton Mains soils —2.8 to 8.3 p.p.m.—is not significantly different from that of the de-

871666—50——3

ficient soils—3.3 to 4.8 p.p.m. Kidson draws the obvious conclusion that there are differences in the availability of cobalt in these soils not detected by the concentrated acid extract, but "with few exceptions the use of dilute acids for cobalt extraction has placed the soils in the same order of cobalt status as that obtained with strong hydrochloric acid. Preliminary experiments have been made with water and carbon dioxide extractions of different soils, but here again the cobalt figures did not provide an explanation of the anomalies under discussion."

Harvey (*84*) and Underwood and Harvey (*182*) likewise came to the conclusion that cobalt surveys have "not been sufficiently comprehensive to justify a decision as to the value of soil cobalt determinations as a guide to 'soundness.'." However, with few exceptions, the cobalt content of "affected" soils is much lower than that of either adjacent "healthy" soils or good soils in other areas (table 4).

TABLE 4.—*Cobalt content of some West Australian soils* [1]

Number of samples	Description of soil	Cobalt in air-dry soil: Average	Cobalt in air-dry soil: Range
	COBALT-DEFICIENT AREAS		
		P. p. m.	*P. p. m.*
5	Wakundup gravelly sand—gray phase	0. 6	0. 5—1. 1
4	Wakundup gravelly sand—brown phase	. 8	. 5—1. 5
2	Wakundup very gravelly sand	1. 1	. 7—1. 5
4	Kordabup sand, variable hardpan, gray sand	. 4	. 2— . 6
4	Kordabup sand, well-defined hardpan, gray-black.	. 3	. 1— . 5
	Average	. 6	. 1—1. 5
	POOR, NON-AGRICULTURAL SOILS ADJACENT TO DEFICIENT AREAS		
5	Plantagenet peaty sand	0. 3	0. 2—0. 5
4	Kwilalup sand, gray sand	. 5	. 4— . 5
2	Willbay sand, gray-black sand	. 2	. 1— . 25
	Average	. 35	. 1— . 5
	"GOOD" AREAS ADJACENT TO DEFICIENT AREAS		
6	Alluvial and wash soils, brown silty sand loam	12. 1	1. 6 —30. 0
4	Scotsdale gravelly loam, reddish-brown sandy loam.	4. 5	2. 0 —10. 0
2	Scotsdale gravelly sand	2. 6	. 15— 5. 0
4	Swamp soils, gray clay or loams	2. 5	1. 5 — 3. 2
3	Laterite boulder areas, gray sandy gravel	1. 0	. 7 — 1. 2
4	Koorrabup gravelly sand, gray sand	1. 0	. 5 — 1. 5
1	Koorundurup gravelly loam, dark chocolate	32. 0	
2	Koorundurup very gravelly sand	1. 7	1. 0 — 2. 5
	Average	5. 7	. 15—32. 0
	"GOOD" AREAS IN OTHER LOCALITIES		
24	Various soils	10. 4	0. 5 —40. 0

[1] From Harvey (*84*).

Noteworthy are the two recordings in table 4 of a cobalt content higher for the loam in a soil series than for the gravelly sand (Scotsdale and Koorundurup). The data are too few, however, to permit any general deductions on the relation of texture to cobalt content.

The data of Bertrand and Mokragnatz (*39*) indicate that the highest cobalt content of the soils they examined is associated with those developed from marls and alluvium. A low cobalt content, however, was not consistently found with any particular formation, with the possible exception of granites (table 1). Kidson (*97*) reported a high cobalt content in soils over serpentine and gabbros and a low content in soils over granite (table 5).

TABLE 5.—*Cobalt content of some soils in Cornwall* [1]

Location of soil	Character of underlying rock	Depth of sample	Cobalt content
		Inches	*P. p. m.*
Goonhilly Down	Serpentine	0–9	8. 0
Do	do	12–24	56. 0
Do	do	30–36	96. 0
Trelanvean	Gabbro-troctolite	0–9	22. 0
Do	do	(2)	11. 0
St. Agnes	Granite	0–6	. 6
Do	do	60–72	4. 3
Tregonning Hill	do	0–6	1. 0
Do	do	6–18	1. 3
Do	do [3]	6–18	0

[1] From Kidson (*97*). [2] Parent rock. [3] Rock fragments.

Kidson noted that "rocks containing little magnesium gave soils with very low cobalt contents," which agrees with evidence already cited. She also noted a marked concentration of cobalt in a concretionary horizon rich in iron in Nigeria. The distribution of cobalt throughout the profile was as follows: Black surface soil (0–13 in.), 13 p. p. m.; concretionary horizon (25–33 in.), 110 p. p. m.; mottled brown and white clay (41–59 in.), 6.3 p. p. m. On the other hand, highly leached soils in Malaya contained extremely small quantities of cobalt, despite the presence of lateritic iron concretions.

In relation to animal diseases in England, Kidson reported that sheep grazing on a soil over granite containing from 2.8 to 3.7 p. p. m. of cobalt suffered from "bush sickness," while those on a soil derived from Devonian conglomerates or Middle Devonian shales containing 11 to 30 p. p. m. of cobalt were healthy. Although the difference between the soils in the two areas is in accordance with the accepted facts on cobalt deficiency, it is also true that the low-cobalt areas contain as much or more cobalt than many good areas in both New Zealand and Australia.

Similar results have been reported from Dartmoor, England, where Mooreland soils on which sheep suffer have a mean cobalt content of 3.9 p. p. m., whereas the lowland soils on which sheep recover have a cobalt content of 16.7 p. p. m. Patterson (*139*) stated in 1938 that all the deficient areas of Dartmoor are on soils derived from granites. He found no evidence of podzolization, "but many of the soils occur on moderately steep slopes, and the constant wash of soil has prevented the development of a mature profile." Good soils derived from shales were decidedly heavier in texture than were deficient soils. Patterson reported that a shale from Marley contained 15 p. p. m. of cobalt, and the soil derived from it 26 p. p. m.

EFFECT OF COBALT ON PLANT GROWTH

Cobalt in Plants Other Than Forages

The presence of cobalt in plants was probably reported for the first time by Legrip (*103*), a pharmacist of Chambon, who stated in 1841 that he found it in the ash of *Lathryus odoratus*. His colleagues, however, "agreed that additional researches should be made to confirm it," which might indicate that they were not yet ready to accept such an unusual phenomenon as a plant containing an element like cobalt. Forchhammer (*72*) reported in 1855 that he had detected cobalt in the ash of oak wood, but not in pine, birch, or any of the marine plants examined. His methods are so clearly described that confidence may be placed in the work. Smith (*167*) reported in 1903 that he had found cobalt in a flowering tree, *Orites excelsa* R. Br., which grows in Australia and New Zealand. However, cobalt was found in only one tree, which had been growing in a district associated with a manganese-cobalt-iron deposit, and this particular sample of wood ash was also high in aluminum, manganese, and iron. Cornec (*57*) reported in 1919 that he had found cobalt in the acid-soluble portion of the ash of laminaries. Vernadsky (*183*) claimed in 1922 to have found cobalt in a number of mosses and other materials in the vicinity of Kiev, Russia.

The first systematic study of the occurrence of cobalt in plants is that of Bertrand and Mokragnatz (*38*), published in 1922. In their examination of 20 samples of the edible portions of plants they found cobalt in all but 1 sample of carrots. They state, however, that their method of analysis was probably not sufficiently sensitive to determine the small quantity of cobalt present in all samples. From their more detailed work (*40*), Bertrand and Mokragnatz summarized their information about the distribution of cobalt in the plant as follows: (1) There is a parallel between the contents of nickel and cobalt in the plant organ in the sense that a small, medium, or large quantity of nickel is accompanied by the same relative quantities of cobalt; (2) the parts of the plant have somewhat the relative standing shown in table 6 with respect to their cobalt contents; (3) the integuments of the grain did not contain more cobalt than did the kernel, at least in the samples of wheat and oats examined. The largest quantity of cobalt reported by these investigators (2.13 p. p. m.) was found in the chanterelle (*Cantharellus cibarius* Fr.), and cobalt, as well as nickel, was present in all plants examined, whether cryptogams or phanerogams.

Other investigators who have reported the presence of cobalt in plants or foods of plant origin include Berg (*36*) in 1925 and McHargue (*110*, *111*) in 1925 and 1927. McHargue detected traces of cobalt in Kentucky bluegrass and in soybean leaves and seeds. Bishop and Lawrenz (*41*) reported in 1932 that cabbage grown in a greenhouse in Norfolk, Cecil, or Hartselle soil gave a green ash of varying intensity, while that grown in Eutaw soil gave a white ash. They

TABLE 6.—*Cobalt content of different parts of a plant (moisture-free basis)* [1]

Relative standing	Part of plant	Cobalt content for several varieties	
		Average	Range
		P. p. m.	*P. p. m.*
1	Leaves	0.19	0.054–0.35
2	Seeds	.08	.002– .36
3	Fruits, roots, and tubers [2]	.06	.005– .20
4	Shells [3]	.006	.003– .010

[1] From Bertrand and Mokragnatz (*40*).
[2] Organs having parenchymatous tissues.
[3] Strongly lignified parts, such as the shells of nuts and fruit stones.

claim to have detected cobalt, but no nickel, in the green or blue ash of these plants. Robinson (*156*), however, has correctly pointed out that this color in the ash was due to manganese and not to cobalt.

Spectroscopic examination of the roots and nodules of several species (*Medicago sativa* L., *Astragalus sinicus* L., *Vicia faba* L., *V. sativa* L., *Trifolium pratense* L., *Ornithopus sativus* Brot., *Lupinus luteus* L., and *Glycine max* Merr.) revealed the presence of cobalt, according to Konishi and Tsuge (*100*). These investigators detected no quantitative differences between the contents of the roots and of the nodules or between species. Ramage (*146*) and Breckpot (*46*) reported the presence of cobalt in plants in 1936—Ramage in St. Ignatius beans, and Breckpot in sugar beets. The more recent investigations of Grimmett (*82*) and of Ahmad and McCollum (*4*) revealed the presence of cobalt in a number of common foodstuffs. Ahmad and McCollum classified their samples according to the State from which they were received. Such a general classification, however, is of no practical value because the soil types are not given, and significant variations in soil types and their effects on plant composition may be greater within the political boundaries of a State than between soils of different States. Hurwitz and Beeson (*90*) have published analyses of the cobalt content of a number of foods of plant origin (tables 7 and 8).

TABLE 7.—*Cobalt content of plants according to species (moisture-free basis)* [1]

Group	Species	Number of samples	Cobalt content
			P. p. m.
I	Spinach	20	[2] 0.67±0.05
II	Mangel-beet leaves	16	.40± .05
	Beet tops	9	.40± .03
	Turnip greens	31	.34± .04
III	Lettuce	11	.21± .07
	Cabbage	14	.19± .03
	Cowpeas	18	.16± .02
IV	Beets (roots)	6	.07± .01
	Sweet potatoes	13	.03± .01
	Corn, field	19	.01± .002

[1] From Hurwitz and Beeson (*90*). [2] Mean with standard error.

TABLE 8.—*Cobalt content of turnip greens, according to natural regions* [1]

Region	Number of samples	Cobalt content
		P. p. m.
East Gulf coastal plain	3	0.10
Atlantic coastal plain	2	.08
Central lowland	2	.43
West Gulf coastal plain	16	.41
New England upland	7	.38

[1] From Hurwitz and Beeson (*90*).

WATER-CULTURE STUDIES WITH COBALT SALTS AND THALLOPHYTA

The effect on thallophytic organisms of cobalt salts, often considered only as metallic poisons in the early literature, has long been a subject of interest and study. One of the earliest reports was made in 1897 by Richards (*149*) who investigated the effects of a number of metal salts, including cobalt, on *Aspergillus niger* and *Penicillium glaucum*. He used double-distilled water and recrystallized his salts and sugar several times. Although these precautions do not necessarily eliminate all cobalt from the culture solution, he reported that additions of cobalt sulfate ($CoSO_4$) up to 0.002 percent increased the growth and weight of the fungus. A concentration of 0.033 percent reduced growth below that made when no cobalt was added.

Ono reported in 1900 (*136*) that in experiments designed to duplicate Richards' conditions that a very small optimum concentration of cobalt favorably influenced growth of algae or of *Aspergillus niger*. The concentration of cobalt most effective for growth of *Hormidium nitens* was 0.12 p. p. m. of the sulfate ($CoSO_4$). Twice this amount gave no greater growth than did the check experiment, and additional increments retarded growth. His results indicate, however, that increasing the cobalt from 17 to 140 p. p. m. of $CoSO_4$ had very favorable effects on the growth of *Aspergillus niger* in culture. Experiments with higher concentration were not reported, so that no optimum concentration was determined for this organism. According to Ono's data, there was a constant decrease in the quantity of acid developed per gram of fungus with increased quantities of cobalt in the culture solution. With the highest concentration of cobalt (140 p. p. m. $CoSO_4$) there was a decrease in the total acid produced. Clarke (*53*) reported in 1899 that a solution of cobalt sulfate, M/256, resulted in normal growth of *Aspergillus flavus* Link, while an M/8 solution was very toxic. Similar ranges were found for a number of fungi, but no favorable effects on growth of solutions of cobalt sulfate as dilute as M/2048 were reported.

Zehl (*193*) in 1908 determined the effect of temperature on the toxicity of cobalt to various organisms. His experiments indicated that the minimum toxic concentration was four times as high as 12° as at 40° C. He also found that the toxicity of cobalt was lower in the presence of other metallic salts, such as nickel and aluminum, and in the presence of boric acid.

Mortensen (*130*) reported in 1909 that no toxic effect on *Aspergillus niger* was noted with concentrations of 0.2 to 3.0 percent of cobalt chloride ($CoCl_2$), but that higher concentrations (3 to 6 percent) increased the time required for sporulation or prevented development of the spore entirely. He stated that in gelatin nutrients 1 percent of $CoCl_2$ was as active as a liquid nutrient containing half that quantity.

According to Javillier (*91*), no action of any kind on the growth of *Sterigmatocystis niger* could be attributed to cobalt in concentrations of 0.1 to 1.0 p. p. m. Steinberg (*172*) reported in 1920 on a series of experiments designed to determine the effect of cobalt and uranium on the growth of *Aspergillus niger*. He added from 0.1 to 50 milligrams of cobalt nitrate ($Co(NO_3)_2$) to a liter of nutrient solution containing, in one set of experiments, 1.0 milligram of ferric phosphate and in another 0.1 milligram of zinc. In the iron experiment, he found that the yield of fungus decreased consistently with increasing additions of $Co(NO_3)_2$, and the sporulation was practically nil. In the zinc experiment an increased yield was obtained with cobalt, but Steinberg states that "the increase obtained in combination with zinc may be due to the presence of traces of iron in the cobalt salt." He failed to find the increase in yields of the fungus claimed by Richards (*149*). Steinberg was the first to use a special method of purification of culture solutions to insure their practical freedom from the element being tested.

Butkewitsch and Orlow (*50*), on the other hand, reported in 1922 that a 0.010 percent solution of cobalt sulfate stimulated growth of *Aspergillus niger*. For the first 4 days the growth in cobalt was less than in the control solution, but at 8 days the fungus grown in the presence of cobalt weighed about 50 percent more than that grown in the control.

Hopkins (*87*) in 1930 reported that cobalt could not replace manganese in the nutrition of *Chlorella*. Mokragnatz (*129*) reported in 1931 that cobalt in concentrations of 1:500 was slightly toxic and in concentrations of 1:250 definitely toxic to *Aspergillus niger*. Concentrations of 1:15,000 to 1:1,500 had very little effect, although there was some evidence of toxic action. Horner and Burk found no evidence that cobalt could replace magnesium (*88*), molybdenum, or vanadium (*89*) in the nutrition of azotobacter. Nielsen and Hartelius (*134*) reported in 1935 that a mixture of a number of elements, including cobalt, stimulated growth of *Aspergillus niger*, but the effect of cobalt alone was not determined. In 1936 Bedford (*31*) defined the toxic limits of cobalt for *A. niger* as being between 1,500 and 1,600 p. p. m. The same limits were reported for *Penicillium oxalicum* and *P. expansum*. Cobalt salts were less toxic to *Penicillium* than mercury or silver salts, but more so than nickel, lead, cadmium, iron, manganese, or zinc. For *Aspergillus* the order was nickel, copper, cobalt, cadmium.

Water- and Sand-Culture Studies With Cobalt Salts and the Higher Plants

There seems to be little evidence, if any, that cobalt in pure culture solutions plays any part in plant metabolism, or that it can in any way be substituted for other cations. Bertrand and Mokragnatz (*40*) and Pereira (*143*) speculated on the possible catalytic action of cobalt in plant cells. Any evidence they suggest, however, is indirect. Lundegårdh and Burström (*105*) reported in 1935 that they could find no evidence that cobalt in concentrations of 0.035 to 0.212 millimol per liter had any effect on the basic respiration factor. Lack of such evidence may be due to difficulties in freeing other salts and materials used in making up the nutrient solutions from minute traces of cobalt present as an impurity, but the indications are that the most minute quantities of cobalt may inhibit plant growth to some extent. A summary of the available information on the effect of cobalt in pure cultures (table 9) shows that while concentrations of one to several parts per million of cobalt in the culture solution were not toxic, a concentration as low as 0.8 p. p. m. prevented normal development of the plant.

TABLE 9.—*Toxic concentrations of cobalt salts as defined by various investigators*

Variety of plant	Cobalt in culture solution	Remarks	Investigator
	P. p. m.		
Corn (*Zea mays*)	None	Blossomed at 55 days; growth normal.	Haselhoff (*85*).
Do	1. 6	Upper leaves colored yellow at end of 10 days; entire plant yellow after 18 days; plant wilted in 31–55 days.	Do.
Do	3. 1	Lower leaves wilted at end of 10 days; tips of leaves turned brown in 18–40 days; plant wilted at 48 days.	Do.
Do	7. 9	Lower leaves wilted at end of 10 days; all leaves turned brown at 18 days; plant wilted at 31 days.	Do.
Beans	None	Normal	Do.
Do	0. 8	Leaves turned yellow with brown tips at 7 days; plant wilted in 30–40 days; no blossoms.	Do.
Do	1. 6	Leaves became yellow, but plant bloomed; blossoms fell off at 12–16 days; plant wilted at 20–40 days.	Do.
Do	3. 1	Similar to 1.6 p. p. m. Co	Do.
Do	7. 9	All leaves strongly yellow at 7 days; bloomed at 12 days; but dropped blossoms at 16 days; plant wilted at 20 days.	Do.
Lupinus alba	2. 3	Limit of toxic action; plant would not grow in solutions containing more than this amount.	Kahlenberg and True (*92*, *93*).
Do	1. 2	Apparently not toxic	Do.
Pisum sativum	9. 2	No growth after 24 hours	Heald (*86*).
Do	4. 6	do	Do.
Do	2. 3	Growth continued second 24 hours.	Do.
Zea mays	18. 4	Toxic	Do.
Do	9. 2	Growth continued second 24 hours.	Do.

TABLE 9.—*Toxic concentrations of cobalt salts as defined by various investigators*—Continued

Variety of plant	Cobalt in culture solution	Remarks	Investigator
	P. p. m.		
Wheat	88	Very toxic	Coupin (*59*).
Pisum sativum	60	Co substituted for Fe in nutrient solution; swelling of roots, but root development slight; several bare spaces and an aborted root growth.	Ducloux and Cobanera (*64*).
Do	600	Definitely toxic	Do.
Wheat	7	Minimum toxic concentration	Free and Trelease (*74*).
Zea mays	147	Toxic	Pirschle (*142*).
Barley	147	do	Do.
Wheat	[1] 2. 9	Minimum concentration showing definite toxicity in sand culture.	Scharrer and Schropp (*162*).
Rye	[1] 2. 9	do	Do.
Barley	[1] 29. 5	do	Do.
Oats	[1] 2. 9	do	Do.
Corn	[1] 29. 5	do	Do.
Peas	[1] 29. 5	do	Do.
Beans, bush	[1] 29. 5	do	Do.
Corn	[1] 2. 9	do	Do.
Do	12. 5	No toxicity noted	Lundegardh and Burström (*105*).
Castor oil	3. 9	No toxicity	Sempio (*164*).
Wheat	589	Extreme toxicity; plant died in 36 hours.	Singh and Prasad (*165*).
Do	295	Severe toxicity; plant died in 7 days.	Do.
Do	29. 5	Mild toxicity; plant died in 3 weeks.	Do.
Do	5. 9	Feeble toxicity; plant completed life cycle, but yield was low.	Do.
Lettuce	. 01	Apparently no toxic effect	Arnon (*6*).
Barley, mature	1	Toxic	Brenchley (*47*).
Do	. 5	No effect on growth	Do.
Broad beans	. 02	Toxic	Do.
Do	. 01	No effect on growth	Do.
Corn	3. 0	do	Bastisse (*27*).
Do	8. 0	Toxic	Do.
Tobacco seedlings.	5. 0	Chlorosis	Spencer (*169*).

[1] In these experiments minute amounts of cobalt retarded plant growth. The limiting values given here indicate the point at which marked diminution of growth occurred.

A few of the results compiled in table 9 will be discussed briefly. Kahlenberg and True (*92*, *93*) and Heald (*86*) undertook to prove by their experiments that "the poisonous property of a very dilute solution is due to the ions it contains, and if at the particular dilution in hand only one physiologically active ion is present, the effectiveness of the solution is to be attributed to that one ion." They tested this theory for a number of ions and determined, for example, that the toxic limit for cobalt as either the sulfate or the nitrate was about 1/12,800 gram equivalent per liter. In a solution more concentrated than this, *Lupinus alba* was killed, or no measurable growth of roots was detected in 24 hours. Experiments such as this, however, are of very limited value, for although root growth may occur in the solution described, yet no evidence was obtained of the effect on the normal growth and development of the plant and its seed. Thus, Haselhoff (*85*) reported in 1895 that corn (*Zea mays*) and beans would grow in solutions containing nearly 8 p. p. m. of cobalt, but the plants eventually wilted and did not bloom, even when grown in solutions containing as little as 1.6 p. p. m. of cobalt. The failure to measure the adverse effects of cobalt solutions on the normal development of the plant through maturity is common to several reports (*74*, *105*, *162*) cited in table 9.

In some investigations (*59*, *64*, *142*) large quantities of cobalt were cited as being toxic, but no attempt was made to determine whether or not smaller quantities were less toxic or did no harm. The only investigators to report on a concentration of cobalt that permitted the normal development of the plant and the seed were Singh and Prasad (*165*). In 1936, they reported that wheat plants did not survive in any cobalt solutions greater than 0.0001 M. In this solution a slight toxicity was noted, but the plants completed their life cycle with earlier ear formation and a lower final dry-matter yield than obtained with the control.

Scharrer and Schropp (*162*) in 1933 measured the growth of a number of species in both sand and water cultures containing cobalts. They noted a slight retardation of growth, even with the most dilute cobalt solution used (10^{-9} milliequivalent of cobalt per liter), in nearly every case, with the possible exception of corn grown in sand culture. The data, except those for peas and beans, however, are variable. Thus, in a sand-culture experiment using a solution containing 10^{-2} milliequivalent of cobalt, a yield equal to or better than that of the control was obtained with wheat, rye, barley, oats, and corn. In every instance, however, yields of dry matter were definitely lower when the concentration of cobalt was 10^{-1} milliequivalent per liter, and a concentration of 1 milliequivalent was definitely toxic. The experiments were not extended to include measurements at maturity of the plants, a very important consideration, for in most of the experiments cited by these investigators the reductions in yields of young plant material appear to be small, and it would be desirable to know what the effects were on yields of grain or seed.

Sempio (*164*) reported in 1935 that in most cases M/15,000 solutions of cobalt showed the ability to inhibit almost entirely the formation of tumors on castor-oil plants inoculated with *Bacterium tumefaciens*. He found that it was necessary before inoculation for the plants to have absorbed a certain quantity of the metal, or rather to be given time to "form organic compounds of cobalt which can eventually exercise strong defensive action." The salts of cobalt themselves apparently had no effect on the organism, for "*Bacterium tumefaciens*, held for more than eight hours in suspension in a M/600 solution of cobalt and streaked on agar, shows scarcely any damage by the metal." The M/15,000 solutions of cobalt did not appear to injure the plant.

Toxic action of cobalt salts was reported also by Němec and Babička (*133*). Maier (*118*), Schropp and Scharrer (*163*), and Arnon (*6*) used cobalt in nutrient solutions. They noted no toxic effects with the very dilute solutions (about 0.01 p. p. m. of cobalt) and in the presence of other elements. No favorable effect was ascribed to the presence of cobalt by Maier (*118*), who studied the elements individually as well as in groups.

Experiments With Cobalt Salts as Soil Amendments

Contrary to the results obtained with pure culture experiments, there have been scattered reports of increased yields from adding cobalt salts to soils. For the most part, however, these results have been negative or even adverse to plant growth. This is to be expected if one considers that if this element is essential it must be so in such small amounts as to be almost impossible of measurement by present methods. It is hardly conceivable that such small quantities, if required, are often lacking in soils in view of the probable widespread occurrence of cobalt. It seems natural, therefore, to expect no positive results from the use of cobalt as a fertilizer.

Fukutome (*75*) reported in 1904 that 0.02 gram of cobalt sulfate per 8 kilograms of soil exerted a stimulating effect on flax. Quantitatively the effect was about the same as that obtained with iron and manganese, and there is no evidence that these two elements were not impurities in the cobalt salt used. Nakamura (*131*) also reported, in 1904, that he had obtained slight stimulative action with 0.01 gram of cobalt nitrate in 2,300 grams of soil. He noted a slight stimulative action on the leaves of *Brassica chinensis*, although the root system was smaller than that of the control. There is no statement as to the purity of the salts he used, and he says "in no case was the stimulating action of any considerable importance." In fact, the number of experiments was so small that the differences might well have been ascribed to experimental error.

The nature of the toxic effect of cobalt on plant growth has been studied by Somers and Shive (*168*). According to these workers, cobalt has a strong tendency to reduce the metabolic efficiency of iron. Thus, a high concentration of cobalt in the nutrient solution reduced the soluble iron in the plant. Consequently, iron deficiency symptoms appeared. Millikan (*124*) has also observed this effect. He reported that 1 milligram of cobalt per liter of nutrient solution induced an iron deficiency chlorosis. This could be prevented by additional iron or by adding 10 mg. of molybdenum per liter. Investigations on the effect of molybdenum on cobalt absorption reported by Oertel, Prescott, and Stephens (*137*) confirm the antagonism of molybdenum in soil as well as in nutrient solution cultures.

According to Petri (*141*) in 1910, cobalt added to the soil in which olive trees were growing had decidedly toxic effects on them. The leaves turned yellow or fell off, and the limbs assumed a dirty yellow color. There was a progressive shortening of the internodes; and the youngest shoots not only were checked in their growth, but several were entirely withered. When cobalt was no longer added to the soil, the symptoms of poisoning disappeared. Roxas (*158*) in 1911 failed to obtain any definite stimulation of rice plants (soil-sand mixture in pots) when cobalt was added in concentrations of M/50,000 to M/1,000. Free (*73*) in 1917 could detect no toxic symptoms in *Pelargonium zonale* grown in soil in the greenhouse when 500 p. p. m. of cobalt sulfate was added.

Gedroitz (*76*), in an obscure Russian journal, claims to have obtained in 1933 a stimulative effect when cobalt and other elements were present in the soil adsorptive complex. It is not clear from the abstract of the report whether the effect of cobalt alone was studied or whether all of the elements were added to the soil together. Knott (*99*) in 1934 added cobalt sulfate ($CoSO_4{\cdot}7H_2O$) to a muck soil in New York at the rate of 300 pounds per acre. He observed no significant effects of cobalt, unless the slightly lower yields obtained were indicative of toxic effects. Purvis and Ruprecht (*144*) state in a brief report that cobalt proved decidedly toxic to celery plants, although a later report (*145*) indicates that a combination of manganese, zinc, and cobalt gave significantly increased yields. The effect of cobalt alone, however, was negative, according to these investigators. Krisciunas (*102*) in 1936 reported that he could find no effect ascribable to cobalt on the yield of sugar beets. Young (*192*) reported in 1935 that cobalt, even in concentrations of 0.1 p. p. m., was slightly detrimental to timothy growing in Merrimac coarse sandy loam in pots. Neither Kessel and Stoate (*95*), in 1936, nor Dunne (*65*), in 1938, could detect any benefit to diseased trees from solutions of cobalt applied to the soil.

Samuel and Piper (*160*) reported in 1929 that manganese was not replaceable by cobalt in plant nutrition. Riceman and Donald (*147*) reported in 1938 that 5 pounds of cobalt chloride per acre had a depressing effect on the growth of wheat, oats, and barley. Rye did not seem to be affected so far as the grain yield was concerned, but the yield of straw was depressed. Zelenov (*194*) could find no beneficial effect of cobalt on the growth of flax or oats. Stewart, Mitchell, and Stewart (*173*) reported that 40 pounds of cobalt chloride ($CoCl_2{\cdot}6H_2O$) per acre had no visible effect on yield of pasture herbage, but that 80 pounds markedly depressed growth of both grasses and clovers.

COBALT IN PASTURE HERBAGE IN RELATION TO ANIMAL GROWTH AND HEALTH

As cobalt is of concern primarily in the nutrition of ruminants, its occurrence in forages is important. By far the most extensive investigations on this subject are reported from New Zealand and Australia, where systematic surveys of deficient areas have been conducted for several years. The general ranges of cobalt supply in forages and their effect on animal health have already been presented. The values that have been reported in the literature are presented in table 10. These values are for pasture herbage, and represent more than one species in most cases. It is apparent that the levels for deficient areas agree with the ranges given on page 6. One set of values, that from the Cheviot Hills of Scotland (*58*), seems unusually high. In general, it is evident that the cobalt content of a pasture is relatively low as compared with the usual levels of other mineral elements, and the range of values reported is, likewise, relatively narrow.

TABLE 10.—*Cobalt content of pastures (moisture-free basis)*

Location	Cobalt in— Good pastures			Cobalt in— Deficient pastures		
	Minimum	Maximum	Average	Minimum	Maximum	Average
	P. p. m.	*P. p. m.*	*P. p. m.*	*P. p. m.*	*P. p. m.*	*P. p. m.*
New Zealand [1] (*116*)	0. 06	0. 12	0. 08	0. 03	0. 04	0. 03
Nelson, New Zealand (*171*)	. 03	. 21	. 07	. 03	. 05	. 04
Sherry River Valley, New Zealand (*9*)	------	------	------	------	------	. 04
Glenhope, New Zealand (*10*)	------	------	------	. 04	. 07	. 05
Do. (*7*)	. 20	1. 00	------	. 03	. 07	------
Nelson, New Zealand (*19*)	. 06	. 25	. 15	. 05	. 07	. 07
Glenhope, New Zealand (*19*)	. 07	. 11	. 09	. 03	. 06	. 04
Morton Mains, New Zealand (*19*)	------	------	------	. 07	. 19	. 14
New Zealand (*20*)	. 06	1. 26	. 26	. 04	. 25	. 09
North Island, New Zealand (*113*)	. 03	. 26	. 11	. 01	. 08	. 04
Denmark District, Australia (*182*)	. 04	. 30	. 13	. 02	. 07	. 04
Do. (*182*)	. 03	. 43	. 18	------	------	------
Do. (*84*)	. 03	. 30	. 16	. 03	. 07	. 06
Australia (*84*)	. 03	. 18	. 13	------	------	------
Cheviot Hills, Scotland (*58*)	tr.	. 20	------	tr.	. 10	------
Wales, England (*175*)	------	------	------	. 02	. 20	. 05
Town of Albany, N. H. (*35*)	. 07	. 08	. 07	. 02	. 08	. 05
Buzzards Bay, Mass. (*35*)	. 10	. 10	. 10	. 03	. 09	. 06
Hoffman Forest, N. C. (*35*)	. 04	. 07	. 06	. 02	. 07	. 04
Arnot Forest, New York (*35*)	. 07	. 12	. 10	------	------	------
Maine [2] (*35*)	. 06	. 08	. 07	------	------	------
Do.[3]	. 07	. 13	. 10	------	------	------
Norway (*67*)	. 07	. 25	------	. 03	. 08	------
Connecticut (*187*)	------	------	------	. 02	. 13	------
Scotland (*42*)	------	------	------	. 02	. 07	------

[1] Limestone soil. [2] Native pasture. [3] Improved pasture.

The data in table 10 indicate that at times the cobalt content of a good pasture may drop significantly below 0.07 p. p. m., while that of "affected" pastures frequently exceeds this amount. The importance of the average value throughout a season must therefore be emphasized. Although the data may be too meager to permit any definite limitations to be set, it is entirely possible that an average value throughout the year greater or less than 0.07 p. p. m. of cobalt might represent the minimum level for health in ruminants. This is the conclusion, at least, that might be drawn from the data in the table. It may be possible that one pasture could supply enough cobalt early in the spring to insure the health of an animal throughout the year, while the value of another pasture might depend upon a more constant but smaller supply throughout the season. Such differences might be expected with differences in climate or soils.

It is of interest, for example, that Harvey (*84*) reported in 1937 that a "healthy" pasture in Brunswick, Western Australia, contained only 0.03 p. p. m. of cobalt, although the average of all healthy pastures was 0.13 p. p. m. Apparently single samples were taken. Also, as Harvey points out, "the plant material does not necessarily provide the only source of elements required for normal health in grazing stock." No estimate has been made, however, of the quantities of trace elements that an animal might obtain directly from the soil. Underwood and Harvey (*182*) state that "it is necessary for animals to be pastured for many months on low-cobalt herbage before signs of deficiency become apparent. It is obvious that where they have occasional access to soils and herbage of much higher cobalt status, no sign of disease could occur."

Effect of Season on Cobalt Content of Herbage

The apparent discrepancies in values for desirable cobalt levels in pasture herbage call for an examination of the published reports on the effect of climate or season. Several investigators have reported incidental studies of this factor. Few, however, seem to have conducted objective studies of the problem in which climatic factors, physiological age of plant, and other possible influences were considered. Consequently, the results are not in agreement. It has been reported generally (*7*, *11*, *14*, *19*, *20*, *125*) that the cobalt content of pastures top-dressed with cobalt is markedly reduced as the season advances and the time after treatment increases. This might be expected to occur as the plant matures, or as the added cobalt disappears or becomes unavailable. Some investigators have reported a slight reduction in cobalt in untreated pastures in the fall as compared with the spring levels (*11*, *20*, *58*, *98*, *117*, *125*). Others (*10*, *11*, *14*, *19*, *121*, *150*) have reported no significant change during the season. McNaught (*113*, *116*) reports a definite minimum value in midsummer, particularly in good pastures.

Beeson, Gray, and Smith (*35*) made a study of the cobalt content of the leaves of *Arundinaria tecta*, a reed used for forage, in North Carolina at monthly intervals for a year. In this study climatic factors were confounded with the age of the plant, and only one part, the leaf, was used for analysis. The data (table 11) show no marked

Table 11.—*Composition of reeds in North Carolina Coastal Plain region (moisture-free basis)*[1]

Date	Calcium at—		Phosphorus at—		Manganese at—		Cobalt at—		Protein at—	
	Wenona	Hoffman Forest	Wenona	Hoffman Forest	Wenona	Hoffman Forest	Wenona	Hoffman Forest	Wenona	Hoffman Forest
1943	*Percent*	*Percent*	*Percent*	*Percent*	*P. p. m.*	*P. p. m.*	*P. p. m.*	*P. p. m.*	*Percent*	*Percent*
Jan. 13	0.46	0.37	0.100	0.071	320	72	0.06	0.02	9.90	9.37
Feb. 13	.39	.46	.118	.076	334	135	.07	.07	10.50	10.64
Mar. 14	.46	.36	.112	.060	507	108	.04	.04	11.57	8.40
Apr. 22	.09	.30	.398	.090	290	120	.07	.06	20.14	9.44
May 22	.15	.18	.284	.138	154	86	.05	.02	18.81	12.06
June 19	.17	.24	.173	.103	121	71	.07	.02	15.68	10.44
July 16	.28	.34	.174	.093	224	88	.06	.05	15.41	10.12
Aug.	.31	.37	.163	.082	205	75	.05	.04	16.44	9.30
Sept.	.34	.46	.153	.086	328	110	.04	.02	14.37	9.30
Oct.	-----	.42	------	.105	------	119	------	.03	------	10.76
Nov. 30	-----	.35	------	.104	------	69	------	.05	------	12.09
1944										
Jan. 4	.35	-----	.078	------	113	------	.06	------	9.65	------

[1] From Beeson, Gray, and Smith (*35*).

changes in cobalt content throughout the year. In general, many of the conclusions on the effect of season or climate are based on a relatively small number of samples and variations that do not depart materially from normal.

Effect of Cobalt Top Dressing on Cobalt Content of Herbage

The difficulties and expense connected with the use of drenches in the treatment of cobalt deficiency diseases led naturally to attempts to increase the cobalt content of pastures by fertilization. For the most part the results have been satisfactory, although, as might be expected from the effect of cobalt salts on plants, the yields of pastures (especially the white clover content) frequently have been depressed (*17, 173, 192*).

Rossiter, Curnow, and Underwood (*157*) made a careful study of the effect of three levels of cobalt per acre on the cobalt content of subterranean clover at three stages of growth. An application of 4 ounces of cobalt sulphate ($CoSO_4{\cdot}7H_2O$) per acre resulted in a sixfold increase in the cobalt content of the clover at bud stage. In general, the application of cobalt had a more dominant effect on cobalt in the plant than did stage of maturity.

Table 12, which summarizes the experience of several investigators with the use of cobalt top dressing, shows that, in general, not more than 2 pounds per acre of a salt such as the chloride ($CoCl_2{\cdot}6H_2O$) is required to prevent cobalt deficiency in sheep. Such an application seems ample for at least one season, and there is some evidence of a longer residual effect.

A cobaltized superphosphate to insure better distribution and greater convenience of handling cobalt salts was proposed by Askew, Rigg, and Stanton (*22*) in 1938. They found that adding cobalt at the rate of 1 pound per hundredweight of superphosphate gave a dry, free-running material. The availability of the phosphorus was reduced slightly, but storage resulted in no reduction in the solubility of the cobalt. Mixing cobalt chloride with basic slag and other materials giving a high pH in water suspension resulted in lowering the solubility of the cobalt, and this was further reduced upon storage. Askew (*8*) has shown that an aqueous extract of 0.1 gram of Cobalt phosphate ($Co_3(PO_4)_2{\cdot}8H_2O$) contains 2.45 micrograms of cobalt in 1 liter. The compound was readily soluble in an aqueous solution at pH 2, however. Several investigators (table 12) have used cobaltized superphosphate with good results. In view of the small quantities of cobalt required and the general use of superphosphate on pastures, the combination seems worth further consideration.

Certain experiences with top dressing to improve the cobalt status of pastures should be emphasized. Some investigators (*1, 17, 127*) have observed that limestone applied with the cobalt resulted in less cobalt being absorbed by the plants. Watson (*189*), however, reported that limestone had no effect on the cobalt content of pasture

TABLE 12.—*Effects of cobalt top dressing on cobalt content of pasture herbage (moisture-free basis)*

Cobalt applied per acre [1] (pounds)	Effect on sheep grazing the pasture	Cobalt content of pasture		Remarks
		Untreated	Treated	
		P. p. m.	*P. p. m.*	
¼	Good (2, 3)			Observed for 2 seasons.
2	Corrected and prevented deficiency (*174*).			
½	Corrected deficiency on granite soils (6).			½ lb. better than ¼ lb.
2	Corrected deficiency (*19*).	0. 05–0. 07	0. 13–0. 20	
10	do			Very deficient area.
¼–½	Good (*43*)	. 06	1. 03	After 1 year 0.14 p. p. m.
2	Good (*173*)	. 11	. 51–0. 83	Amounts beyond this not economical.
⅛–¼	Good (*14*)			
⅛–1	Good (*12*)			Effective through 2 seasons.
½–1	Good (*63, 151*)			Cobaltized superphosphate.
⅒–2	-- (*182*)	. 08	. 22–0. 96	Increased Co content of *Trifolium subterraneum* several fold.
1	Corrected deficiency; improved wool (*14*)	. 03	1. 02	Cobaltized superphosphate.
¼–2	-- (*150*)			Increased Co in pasture.
2	Corrected deficiency for 2 seasons (*125*).			Do.
10	Good (*61*)			Top-dressed pasture contained 12 times as much Co as control.
1⁹⁄₁₀	-- (*115*)		2. 00	Effective increase in Co content of pasture for 6 months.
½	Good (*114*)	. 02	. 20	
10–100	-- (*7, 17*)	. 22–1. 26	4. 2–37. 7	
2	Striking improvement within 30 days (*11, 19*).	. 20	6. 7	Granite soil.
2–80	-- (*128*)	. 08	. 22–3. 20	
2–112	-- (*20*)	1. 26	6. 45–37. 7	
1⅒	-- (*98*)			Increase in Co content of various crops.

[1] Generally $CoCl_2 \cdot 6H_2O$.

herbage. Rigg (*151*) found that 3 tons of ground limestone containing approximately 5 p. p. m. of cobalt caused an increase in the cobalt content of pasture equal to that of an application of 4 ounces of the sulfate. Askew (*13*), however, observed that lambs developed deficiency symptoms when pastured on herbage that had been limed with material low in cobalt. The pasture treated with superphosphate alone was superior in cobalt content to the limed pasture. Beeson, Gray, and Hamner, (*34*) observed that liming did not depress the absorption of cobalt by soybeans from the Norfolk fine sand. The normal cobalt content of this soil is very low, and the soybeans contained 0.02 p. p. m. of cobalt in the dry material. However, if soluble cobalt salts were added with the limestone less cobalt was absorbed by the plant than in the absence of limestone.

Two applications of 2 ounces each of cobalt sulfate per acre in two successive seasons gave slightly better results than one application of 4 ounces, according to Askew (*14*). At the end of the first season, the 4-ounce application showed a superiority over the smaller one. The effect on the live-weight increase of sheep with cobaltized superphosphate, which provided 16 ounces of cobalt sulfate per acre, was more pronounced and extended through three seasons. Further reports by Askew (*15*) support the practicability of using 4 to 5 ounces of cobalt sulfate ($CoSO_4{\cdot}7H_2O$) per acre, although applications of 2 ounces each in two consecutive years gave better results than a single 4-ounce application.

Askew (*12*, *23*) reported also that there is no evidence that the sulfate, carbonate, and phosphate of cobalt differ as top-dressing material. He noted that 500 to 1,000 pounds of serpentine was satisfactory as a cobalt carrier. Maunsell and Simpson (*123*) found that satisfactory carriers of cobalt include double superphosphate, a reverted (15 percent lime) superphosphate, various mixtures of superphosphate and lime, serpentine and superphosphate, beach sand, pumice sand, and a water solution. Andrews and Prichard (*5*) were successful in applying a water solution of cobalt by spraying it from an airplane. They top-dressed the soil at the rate of 20 ounces of commercial cobalt sulfate per acre, using a saturated solution of the salt. They found that cobalt can be distributed over flat country evenly and accurately under calm weather conditions. Winds up to 15 miles an hour did not interefere.

Effect of Different Plant Species on Cobalt Content of Pasture Herbage

Askew and Dixon (*17*) grew dogstail, ryegrass, and sweetclover in pots. The cobalt content of dogstail was slightly lower than that of either of the other two species. Kidson and Maunsell (*98*) reported very little difference in the cobalt content of rape leaves and turnip leaves, but they found much less cobalt in the oat plant. These materials had been grown in outdoor plots. Mitchell (*125*) found both oat straw and grain very low in cobalt, as compared with ryegrass or red clover, with timothy intermediate. Beeson, Gray, and Adams (*33*) determined the cobalt content of a number of common grasses, all grown under uniform conditions (table 13). Timothy, one of the most common constituents of hay in the northern United States, is very low in cobalt in comparison with other grasses.

TABLE 13.—*Cobalt content of grasses grown on Dunkirk fine sandy loam, first cutting (moisture-free basis)*[1]

Grasses	*Cobalt content*[2]
	P. p. m.
High-cobalt group:	
Kentucky bluegrass (II)[3]	0. 13±0. 01
Kentucky bluegrass (I)[4]	. 14± . 02
Carpet grass[4]	. 13± . 02
Medium-cobalt group:	
Bromegrass[5]	. 09± . 01
Quackgrass[5]	. 09± . 01
Bahia grass (I)	. 08± . 01
Johnson grass	. 08± . 01
Bahia grass (II)	. 08± . 01
Vasey grass	. 08± . 01
Redtop	. 08± . 01
Timothy	. 08± . 01
Orchard grass	. 08± . 01
Low-cobalt group:	
Para grass	. 07± . 01
Dallis grass	. 07± . 01
Bermuda grass	. 07± . 01
Natal grass	. 05± . 01

[1] From Beeson, Gray, and Adams (*33*).
[2] Mean and standard error.
[3] Significantly different from bromegrass at the 1-percent level.
[4] Significantly different from para grass at the 1-percent level.
[5] Significantly different from natal grass at the 1-percent level.

RELATION BETWEEN SOIL COBALT AND COBALT CONTENT OF PASTURE HERBAGE

Askew and Maunsell (*20*) could find no relationship between the cobalt content of the soil and that of the pasture herbage growing thereon. For example, herbage on a Nelson soil containing 41 p. p. m. of cobalt was lower in cobalt throughout the season than that growing on an Appleby soil containing 18 p. p. m. of cobalt. This was later confirmed in the work of Stanton and Kidson (*171*). They grouped these soils into three classes and found that the cobalt content of the herbage increased slightly, but not proportionally, as the cobalt content of the soil group increased (table 14).

TABLE 14.—*Relation of soil cobalt to cobalt content of New Zealand pasture herbage (moisture-free basis)*[1]

Group	Cobalt in soil			Cobalt in herbage		
	Maximum	Minimum	Average	Maximum	Minimum	Average
	P. p. m.	*P. p. m.*	*P. p. m.*	*P. p. m.*	*P. p. m.*	*P. p. m.*
I	2. 0	0. 7	1. 2	0. 07	0. 03	0. 04
II	4. 9	2. 1	3. 4	. 12	. 03	. 06
III	19. 4	5. 2	9. 2	. 21	. 03	. 08

[1] From Stanton and Kidson (*171*).

Mitchell (*126*), however, feels that variations in the cobalt content of vegetation due to sampling difficulties, season, or contamination are so important that there is a distinct advantage in taking soil samples in order to evaluate a region in terms of its cobalt status. He suggests for this purpose a 2.5 percent solution of acetic acid and proposes a separation between good and deficient soils at 0.25 to 0.30 p. p. m. of cobalt. The classification of plants according to their cobalt content, however, is based on many factors of which the quantity of cobalt present in the soil is only one. It is doubtful, therefore, if soil tests will ever be as precise and discriminating as are vegetation tests. The plant summarizes all the factors responsible for its cobalt content. It must thus be the ultimate criterion of the ability of a soil to supply this element so essential to the ruminant.

SUMMARY

A nutritional disturbance in ruminants that can be corrected by administering cobalt occurs in various parts of the world, including several sections of eastern and northern United States.

No specific clinical symptoms that permit a direct diagnosis of a case of cobalt deficiency have been noted in ruminants. The most common criterion seems to be the recovery of sick animals when cobalt is given to them.

The minimum daily cobalt requirement for sheep seems to be about 0.1 mg. This is the quantity necessary for growth and general health. The additional quantities required for reproduction and lactation have not been determined. Cattle appear to have a lower requirement for cobalt per unit of body weight than sheep, but few quantitative measurements have been made.

A forage containing 0.10 to 0.13 p. p. m. of cobalt in the dry matter would supply a daily minimum requirement of 0.1 mg. of cobalt for sheep. Sheep fed forage containing more than 0.07 p. p. m. of cobalt on an avearge do not seem to require a cobalt supplement.

The cobalt content of minerals and rocks seems to follow certain recognized principles. Thus, cobalt will be found in association with magnesium, nickel, and iron because of radii of similar magnitudes. The evidence that cobalt is found in greater concentrations in basic rocks than in acidic rocks such as granites is clear.

The cobalt content of soils is a variable quantity that depends somewhat on the cobalt content of the parent rock. However, the concentration in a residual limestone soil may be very high, although the original limestone may be much lower in cobalt. It is apparent that soil-forming factors have an important role in determining the cobalt content of a soil.

No clear evidence of a close relationship between the cobalt content of the soil and that of the plant or the occurrence of cobalt deficiency in animals has been presented. No successful attempt to determine the cobalt compounds of the soil that are available to the plant has been made.

The evidence as to the effect of cobalt on the growth of Thallophyta is not clear. There seems to be none, however, that cobalt has any favorable effect on the growth of higher plants. Retarded growth and toxicity symptoms have been observed where excessive quantities of cobalt have been supplied to the plants.

There is as yet no clear evidence of any marked effect of climate or season on the cobalt content of forage.

The use of cobalt salts or superphosphate-cobalt mixtures for top dressing pastures has proved an effective method for the cure and prevention of cobalt deficiency. The benefits, however, seldom last for more than two seasons.

LITERATURE CITED

(1) ANONYMOUS.
1943. MINERAL CONTENT OF PASTURES—INVESTIGATIONS AT THE CAWTHRON INSTITUTE. New Zeal. Dept. Sci. and Indus. Res. Ann. Rpt. **17**: 10–11.

(2) ———
1944. MINERAL CONTENT OF PASTURES. New Zeal. Dept. Sci. and Indus. Res. Ann. Rpt. 18: 19.

(3) ———
1945. COBALT INVESTIGATIONS. Cawthron Inst. Sci. Res. Ann. Rpt. 1944–45: 7.

(4) AHMAD, BASHIR, and MCCOLLUM, E. V.
1939. THE COBALT CONTENT OF FOOD MATERIALS FROM DIFFERENT PARTS OF THE UNITED STATES. Amer. Jour. Hyg. 29A: 24–26.

(5) ANDREWS, E. D., and PRICHARD, A. M.
1947. TOP-DRESSING COBALT-DEFICIENT LAND FROM THE AIR. New Zeal. Jour. Agr. 75: 501, 503–506, illus.

(6) ARNON, D. I.
1938. MICROELEMENTS IN CULTURE-SOLUTION EXPERIMENTS WITH HIGHER PLANTS. Amer. Jour. Bot. 25: 322–325, illus.

(7) ASKEW, H. O.
1936–37. MINERAL CONTENT OF PASTURES. REPORT OF STOCK AND PASTURE INVESTIGATIONS IN THE NELSON DISTRICT, 1936–37. New Zeal. Dept. Sci. and Indus. Res. Ann. Rpt. 11: 46–47.

(8) ———
1938. EFFECT OF PH VALUE ON SOLUBILITY OF COBALT PHOSPHATE. New Zeal. Jour. Sci. and Technol. 20A: 106–109, illus.

(9) ———
1938. THE VALUE OF COBALT SUPPLEMENTS FOR BREEDING-EWES AT SHERRY RIVER, NELSON. New Zeal. Jour. Sci. and Technol. 20A: 192–196, illus.

(10) ———
1939. COBALT DEFICIENCY AT GLENHOPE, NELSON, NEW ZEALAND. New Zeal. Jour. Sci. and Technol. 20A: 302–309, illus.

(11) ———
1939. SUCCESSFUL USE OF COBALT SALTS FOR PASTURE TOP-DRESSING IN THE TREATMENT OF STOCK AILMENT AT GLENHOPE, NELSON. New Zeal. Jour. Sci. and Technol. 20A: 315–318, illus.

(12) ———
1942. MINERAL CONTENT OF PASTURES. INVESTIGATIONS AT THE CAWTHRON INSTITUTE. New Zeal. Dept. Sci. and Indus. Res. Ann. Rpt. 16: 13–15.

(13) ———
1943. ANIMAL TESTS WITH COBALT-CONTAINING LIMESTONES AT SHERRY RIVER, NELSON, NEW ZEALAND. New Zeal. Jour. Sci. and Technol. 25A: 154–161, illus.

(14) ———
1944. THE CONTROL OF COBALT DEFICIENCY AT SHERRY RIVER, NELSON. THE VALUE OF MINUTE QUANTITIES OF COBALT SULFATE. New Zeal. Jour. Sci. and Technol. 26A: 216–222, illus.

(15) ———
1946. THE EFFECTIVENESS OF SMALL APPLICATIONS OF COBALT SULFATE FOR THE CONTROL OF COBALT DEFICIENCY IN THE SHERRY VALLEY, NELSON. New Zeal. Jour. Sci. and Technol. 28A: 37–43, illus.

(16) ——— and DIXON, J. K.
1936. THE IMPORTANCE OF COBALT IN THE TREATMENT OF CERTAIN STOCK AILMENTS IN THE SOUTH ISLAND, NEW ZEALAND. New Zeal. Jour. Sci. and Technol. 18: 73–92, illus.

(17) ——— and DIXON, J. K.
1937. INFLUENCE OF COBALT TOP-DRESSING ON THE COBALT STATUS OF PASTURE PLANTS. New Zeal. Jour. Sci. and Technol. 18: 688–693.

(18) ——— and DIXON, J. K.
1937. COBALT STATUS OF ANIMAL ORGANS FROM SOUTH ISLAND (N. Z.) DRENCH EXPERIMENTS. New Zeal. Jour. Sci. and Technol. 18: 707–716.

(19) ——— and DIXON, J. K.
1937. THE VALUE OF COBALT SALTS FOR PASTURE TOP-DRESSING IN THE TREATMENT OF STOCK AILMENT AT GLENHOPE, NELSON, AND MORTON MAINS, SOUTHLAND. New Zeal. Jour. Sci. and Technol. 19: 317–325, illus.

(20) ——— and MAUNSELL, P. W.
1937. THE COBALT CONTENT OF SOME NELSON PASTURES. New Zeal. Jour. Sci. and Technol. 19: 337–342.

(21) ——— and RIGG, T.
1932. OCCURRENCE OF BUSH SICKNESS AT GLENHOPE, NELSON, NEW ZEALAND. New Zeal. Dept. Sci. and Indus. Res. Bull. 32: 1–20, illus.

(22) ——— RIGG, T., and STANTON, D. J.
1938. COBALTIZED SUPERPHOSPHATE. New Zeal. Jour. Sci. and Technol. 20A: 82–89.

(23) ——— and WATSON, J.
1946. THE EFFECT OF VARIOUS COBALT COMPOUNDS ON THE COBALT CONTENT OF A NELSON PASTURE. New Zeal. Jour. Sci. and Technol. 28A: 170–172.

(24) ASTON, B. C.
1924. THE CHEMISTRY OF BUSH SICKNESS, OR IRON STARVATION, IN RUMINANTS. New Zeal. Inst. Trans. 55: 720–723.

(25) ———
1932. IRON LICKS FOR BUSH SICKNESS. New Zeal. Dept. Agr. Jour. 44: 171–176, illus.

(26) BALTZER, A. C., KILLHAM, B. J., DUNCAN, C. W., and HUFFMAN, C. F.
1941. A COBALT-DEFICIENCY DISEASE OBSERVED IN SOME MICHIGAN DAIRY CATTLE. Mich. Agr. Expt. Sta. Quart. Bul. 24: 68–70.

(27) BASTISSE, E. M.
1946. ROLE VECTEUR DE DIVERS ANIONS MINÉRAUX OU ORGANIQUES DANS LES PHÉNOMÈNES GÉOCHIMIQUES ET PHYSIOLOGIQUES. Ann. Agron. [Paris] 16: 434–446.

(28) BECKER, R. B., ERWIN, T. C., and HENDERSON, J. R.
1946. RELATION OF SOIL TYPE AND COMPOSITION TO THE OCCURRENCE OF NUTRITIONAL ANEMIA IN CATTLE. Soil Sci. 62: 383–392.

(29) ——— and HENDERSON, J. R.
1940. THE WELFARE OF CATTLE ON FLORIDA PASTURES. Amer. Soc. Agron. Jour. 32: 185–189.

(30) ——— NEAL, W. M., and SHEALY, A. L.
1931. SALT SICK, ITS CAUSE AND PREVENTION. Fla. Agr. Expt. Sta. Bul. 231: 5–11, illus.

(31) BEDFORD, C. L.
1936. MORPHOLOGICAL AND PHYSIOLOGICAL STUDIES UPON A PENICILLIUM SP. TOLERANT TO COPPER SULFATE. Zentbl. f. Bakt. [etc.], Abt. II, 94: 102–112.

(32) BEESON, K. C.
1945. THE OCCURRENCE OF MINERAL NUTRITIONAL DISEASES OF PLANTS AND ANIMALS IN THE UNITED STATES. Soil Sci. 60: 9–13, illus.

(33) ——— GRAY, LOUISE, and ADAMS, MARY B.
1947. THE ABSORPTION OF MINERAL ELEMENTS BY FORAGE PLANTS. I. THE PHOSPHORUS, COBALT, MANGANESE, AND COPPER CONTENT OF SOME COMMON GRASSES. Amer. Soc. Agron. Jour. 39: 356–362.

(34) ——— GRAY, LOUISE, and HAMNER, K. C.
1948. THE ABSORPTION OF MINERAL ELEMENTS BY FORAGE CROPS. II. THE EFFECT OF FERTILIZER ELEMENTS AND LIMING MATERIALS ON THE CONTENT OF MINERAL NUTRIENTS IN SOYBEAN LEAVES. Amer. Soc. Agron. Jour. 40: 553–562, illus.

(35) ——— GRAY, LOUISE, and SMITH, S. E.
1944. SOME AREAS IN EASTERN UNITED STATES ASSOCIATED WITH DEFICIENCIES OF COBALT AND OTHER ELEMENTS IN THE SOIL. Soil Sci. Soc. Amer. Proc. 9: 164–168.

(36) BERG, RAGNAR.
1925. DAS VORKOMMEN SELTENER ELEMENTS IN DEN NAHRUNGSMITTELN UND MENSCHLICHEN AUSSCHEIDUNGEN. Biochem. Ztschr. 165: 461–462.

(37) BERTRAND, G., and MOKRAGNATZ, M.
1922. SUR LA PRÉSENCE SIMULTANÉE DU NICKEL ET DU COBALT DANS LA TERRE ARABLE. Soc. Chim. de France Bul. 31: 1330–1333. [Cf. SUR LA PRÉSENCE DU COBALT ET DU NICKEL DANS LA TERRE ARABLE. [Paris] Acad. des Sci. Compt. Rend. 175: 112–114 (1922).]

(38) ——— and MOKRAGNATZ, M.
1922. SUR LA PRÉSENCE DU COBALT ET DU NICKEL CHEZ LES VEGETAUX. [Paris] Acad. des Sci. Compt. Rend. 175: 458–460.

(39) ——— and MOKRAGNATZ, M.
1924. SUR LA PRÉSENCE GÉNÉRALE DU NICKEL ET DU COBALT DANS LA TERRE ARABLE. Ann. Sci. Agron. 42: 167–171. [Cf. PRÉSENCE GÉNÉRALE DU NICKEL ET DU COBALT DANS LA TERRE ARABLE. [Paris] Acad. des Sci. Compt. Rend. 179: 1566–1569 (1924).]

(40) ——— and MOKRAGNATZ, M.
1930. RECHERCHES SUR LA PRÉSENCE DU NICKEL ET DU COBALT CHEZ LES VEGETAUX. Soc. Chim. de France Bul. 37: 554–558. [Cf. SUR LA RÉPARTITION DU NICKEL ET DU COBALT DANS LES PLANTES. Soc. Chim. de France Bul. (4) 47: 326–331 (1930). RÉPARTITION DU NICKEL ET DU COBALT DANS LES PLANTES. [Paris] Acad. des Sci. Compt. Rend. 190: 21–25 (1930).]

(41) BISHOP, EDNA R., and LAWRENZ, MARGARET.
1932. COBALT IN PLANT ASH. Science 75: 264–265.

(42) BODDIE, GEORGE F.
1947. TRACE ELEMENT DEFICIENCY IN LIVESTOCK IN THE HEBRIDES. Jour. Compar. Path. and Ther. 57: 52–61, illus.

(43) BONNER, W. G., MCNAUGHT, K. J., and PAUL, G. W.
1939. COBALT TOP-DRESSING EXPERIMENTS. New Zeal. Jour. Agr. 58: 493–494.

(44) BOWSTEAD, J. E., and SACKVILLE, J. P.
1939. STUDIES WITH A DEFICIENT RATION FOR SHEEP. I. EFFECT OF VARIOUS SUPPLEMENTS. II. EFFECT OF A COBALT SUPPLEMENT. Canad. Jour. Res. 17D: 15–28, illus.

(45) BRAY, J. M.
1942. SPECTROSCOPIC DISTRIBUTION OF MINOR ELEMENTS IN IGNEOUS ROCKS FROM JAMESTOWN, COLORADO. Geol. Soc. Amer. Bul. 53: 765–814.

(46) BRECKPOT, RAYMOND.
1936. DÉTERMINATION SPECTROGRAPHIQUE DE CERTAINS ÉLÉMENTS MINEURS DANS LA BETTERAVE SUCRIÉRE. Agricultura (Univ. Louvain) 39 (2): 115–122.

(47) BRENCHLEY, W. E.
1938. COMPARATIVE EFFECTS OF COBALT, NICKEL AND COPPER ON PLANT GROWTH. Ann. Appl. Biol. 25: 671–694, illus.

(48) BRONGNIART, ALEXANDRE.
1836. NOTE SUR LA PRÉSENCE DE QUELQUES MÉTAUX DANS LES GRÈS SUPERIÉURS DU TERRAIN DE PARIS. [Paris] Acad. des Sci. Compt. Rend. 2: 221–225.

(49) BRYAN, O. C., and BECKER, R. B.
1935. THE MINERAL CONTENT OF SOIL TYPES AS RELATED TO "SALT SICK" OF CATTLE. Amer. Soc. Agron. Jour. 27: 120–127, illus.

(50) BUTKEWITSCH, WL., and ORLOW, FR. W. G.
1922. ZUR FRAGE NACH DEN "OKONOMISCHEN KOEFFIZIENTEN" BEI ASPERGILLUS NIGER. Biochem. Ztschr. 132: 556–565.

(51) CARROLL, D.
1941. MINOR ELEMENTS IN MINERALS. Austral. Jour. Sci. 3: 158–160.

(52) ———
1945. MINERALOGY OF SOME SOILS FROM DENMARK, WESTERN AUSTRALIA. Soil Sci. 60: 413–426, illus.

(53) CLARK, J. F.
1899. ON THE TOXIC EFFECT OF DELETERIOUS AGENTS ON THE GERMINATION AND DEVELOPMENT OF CERTAIN FILAMENTOUS FUNGI. Bot. Gaz. 28: 289–327, 378–404, illus.

(54) Clarke, Frank W.
1924. The data of geochemistry. 5th edition. U. S. Geol. Survey Bul. 770, 841 pp.
(55) ——— and Washington, Henry S.
1922. The average chemical composition of igneous rocks. Natl. Acad. Sci. Proc. 8: 108–115.
(56) ——— and Washington, Henry S.
1924. The composition of the earth's crust. U. S. Geol. Survey Prof. Paper 127, 117 pp.
(57) Cornec, Eugéne.
1919. Étude spectrographique des cendres de plantes marines. [Paris] Acad. des. Sci. Compt. Rend. 168: 513–514.
(58) Corner, Harold Hartman, and Smith, Alexander Martin.
1938. The influence of cobalt on pine disease in sheep. Biochem. Jour. 32: 1800–1805.
(59) Coupin, Henri.
1901. Sur la toxicité comparée des composes du nickel et du cobalt a l'égard des vegetaux supérieurs. Soc. de Biol. [Paris] Compt. Rend. 53: 489–490.
(60) Crocker, R. L.
1946. Post-miocene climatic and geologic history and its significance in relation to the genesis of the major soil types of South Australia. Austral. Council Sci. and Indus. Res., Bul 193: 56 pp., illus.
(61) Dixon. J. K.
1936–37. Mineral content of pastures. Report on Morton Mains investigations. New Zeal. Dept. Sci. and Indus. Res. Ann Rpt. 11: 47–49.
(62) ———
1937. The value of nickel salts in the treatment of Morton Mains ailment. New Zeal. Jour. Sci. and Technol. 19: 326–329, illus.
(63) Dixon, J. K., and Kidson, E. B.
1940. The influence of Southland limestones on the cobalt content of pasture at Morton Mains. New Zeal. Jour. Sci. and Technol. 22A: 1–6.
(64) Ducloux, Enrique Herrero, and Cobanera, Maria Luisa.
1911–12. Datos sobre la accion de las de cobalto y vanadio en los vegetales. La Plata Mus. Rev. 18: 145, illus.
(65) Dunne, T. C.
1938. "Wither tip" or "summer dieback". A copper deficiency disease of apple trees. West. Austral. Dept. Agr. Jour. 15: 120–126, illus.
(66) Ender, Fredrik.
1946. Koboltmangelens betydning som sykdomsårsak hos storfe og sau belyst ved terapeutiske forsøk. Norsk Vet. Tidsskr. 58: 118–143.
(67) ——— and Tananger, W.
1946. Fortsatte undersøkelser over årsaksforholdend ved mangel-sykdommer hos storfe og sau. Koboltmangel som sykdom-sårsak belyst ved kjemiske undersøkelser av foret. Norsk Vet. Tidsskr. 9–10: 313–384.
(68) Filmer, J. F.
1933. Enzootic marasmus of cattle and sheep. Austral. Vet. Jour. 9: 163.
(69) ——— and Underwood, E. J.
1934. Treatment with limonite fractions. Austral. Vet. Jour. 10: 83–92.
(70) ——— and Underwood, E. J.
1936. Wasting disease. Diagnosis, prevention, and treatment. West Austral. Dept. Agr. Jour. 13: 199–201.
(71) ——— and Underwood, E. J.
1937. Enzootic marasmus. Further data concerning the potency of cobalt as a curative and prophylactic agent. Austral. Vet. Jour. 13: 57–64, illus.
(72) Forchhammer, J. G.
1855. Ueber den Einfluss des Kochsalzes auf die Bildung der Mineralien. Poggendorff Ann. der Phys. u. Chem. 95: 60–96.

(73) FREE, E. E.
1917. SYMPTOMS OF POISONING BY CERTAIN ELEMENTS IN PELARGONIUM AND OTHER PLANTS. Johns Hopkins Univ. Cir. (n. s.) 3 : 195–198.
(74) ——— and TRELEASE, S. F.
1917. THE EFFECT OF CERTAIN MINERAL POISONS ON YOUNG WHEAT PLANTS IN THREE-SALT NUTRIENT SOLUTIONS. Johns Hopkins Univ. Cir. (n. s.) 3 : 199–201.
(75) FUKUTOME, Y.
1904. ON THE INFLUENCE OF MANGANESE SALTS ON FLAX. Tokyo Imp. Univ. Col. Agr. Bul. 6 : 137–138.
(76) GEDROITZ, K. K.
1932–33. EXCHANGEABLE CATIONS IN THE SOIL AND THE PLANT. III. INFLUENCE ON CROP YIELDS OF MANGANESE, ALUMINUM, AND CERTAIN OTHER METALS INTRODUCED IN VARYING AMOUNTS INTO THE ADSORPTIVE COMPLEX OF SOILS. Mineral Manuring (U. S. S. R.) 1 (109) : 70. [Abstract in Chem. Abs. 28 : 4516.]
(77) GEYER, R. P., RUPEL, I. W., and HART, E. B.
1945. COBALT DEFICIENCY IN CATTLE IN THE NORTHEASTERN REGION OF WISCONSIN. Jour. Dairy Sci. 28 : 291–296, illus.
(78) GOLDSCHMIDT, V. M.
1937. THE PRINCIPLES OF DISTRIBUTION OF CHEMICAL ELEMENTS IN MINERALS AND ROCKS. [London] Chem. Soc. Jour. 1937 : 655–673.
(79) GRANGE, L. I., TAYLOR, N. H., RIGG, T., and HODGSON, L.
1932. THE OCCURRENCE OF BUSH SICKNESS ON THE VOLCANIC SOILS OF THE NORTH ISLAND. New Zeal. Dept. Sci. and Indus. Res. Bul. 32: 21–51, illus.
(80) GREIG, J. R., DRYERRE, H., GODDEN W., and CRICHTON, A.
1933. "PINE": A DISEASE AFFECTING SHEEP AND YOUNG CATTLE. Vet. Jour. 89 : 99–110, illus.
(81) ——— DRYERRE, H., CORNER, H. H., and SMITH, A. M.
1938. BORDER PINE. Vet. Jour. 94 : 335–341.
(82) GRIMMETT, R. E. R.
1937. DEFICIENCY DISEASES OF LIVESTOCK. New Zeal. Dept. Agr. Ann. Rpt. 1936–37 : 47–48.
(83) ——— and SHORLAND, F. B.
1934. SOME CHARACTERISTICS OF "LIMONITES" USED IN THE CURE AND PREVENTION OF BUSH SICKNESS. Roy. Soc. New Zeal. Trans. and Proc. 64 : 191–213, illus.
(84) HARVEY, R. J.
1937. THE DENMARK WASTING DISEASE. COBALT STATUS OF SOME WEST AUSTRALIA SOILS. COBALT STATUS OF PASTURES. West. Austral. Dept. Agr. Jour. (2) 14 : 386–393, illus.
(85) HASELHOFF, E.
1895. VERSUCHE ÜBER DIE SCHÄDLICHS WIRKUNG VON KOBALTHALTIGEM WASSER AUF PFLANZEN. Landw. Jahrb. 24 : 959–961.
(86) HEALD, F. D.
1896. ON THE TOXIC EFFECT OF DILUTE SOLUTION OF ACIDS AND SALTS UPON PLANTS. Bot. Gaz. 22 : 125–153.
(87) HOPKINS, E. F.
1930. MANGANESE, AN ESSENTIAL ELEMENT FOR A GREEN ALGA. Amer. Jour. Bot. 17 : 1047.
(88) HORNER, C. KENNETH, and BURK, DEAN.
1934. MAGNESIUM, CALCIUM, AND IRON REQUIREMENTS FOR GROWTH OF AZOTOBACTER IN FREE AND FIXED NITROGEN. Jour. Agr. Res. 48 : 981–995, illus.
(89) ——— BURK, DEAN, ALLISON, F. E., and SHERMAN, M.
1942. NITROGEN FIXATION BY AZOTOBACTER AS INFLUNCED BY MOLYBDENUM AND VANADIUM. Jour. Agr. Res. 65 : 173–193, illus.
(90) HURWITZ, CHARLES, and BEESON, K. C.
1944. COBALT CONTENT OF SOME FOOD PLANTS. Food Res. 9 : 348–357.
(91) JAVILLIER, M.
1912. SUR LA SUBSTITUTION AU ZINC DE DIVERS ÉLÉMENTS CHIMIQUES POUR LA CULTURE DU STERIGMATOCYSTIS NIGRA. [Paris] Acad. des Sci. Compt. Rend. 155 : 1551–1552.
(92) KAHLENBERG, LOUIS, and TRUE, RODNEY H.
1896. ON THE TOXIC ACTION OF DISSOLVED SALTS AND THEIR ELECTROLYTIC DISSOCIATION. Bot. Gaz. 22 : 81–124.

(93) ——— and True, Rodney H.
1896. On the toxic action of dissolved salts and their electrolytic dissociation. Amer. Med. Assoc. Jour. 27: 138–141.
(94) Keener, H. A., Percival, G. P., and Morrow, K. S.
1944. Cobalt treatment of a nutritional disease in New Hampshire dairy cattle. N. H. Agr. Expt. Sta. Cir. 68.
(95) Kessell, S. L., and Stoate, T. N.
1936. Plant nutrients and pine growth. Austral. Forestry 1: 4–13.
(96) Kidson, E. B.
1937. Cobalt status of New Zealand soils. New Zeal. Jour. Sci. and Technol. 18: 694–707.
(97) ———.
1938. Some factors influencing the cobalt content of soils. Soc. Chem. Indus. Trans. Jour. 57: 95–96.
(98) ——— and Maunsell, P. W.
1939. The effect of cobalt compounds on the cobalt content of supplementary fodder crops. New Zeal. Jour. Sci. and Technol. 21A: 125–128.
(99) Knott, J. E.
1934. The effects of certain salts on the growth of onions. Amer. Soc. Hort. Sci. Proc. 32: 561–563.
(100) Konishi, Kametaro, and Tsuge, Toshihisa.
1936. On the mineral matters of certain leguminous crops. I. Inorganic constituents of underground plant parts of certain leguminous crops. Kyoto Univ., Col. Agr. Mem. (Chem. Ser. 20) 37: 1–24.
(101) Kraut, K.
1906. Über die Verbreitung des Nickels and Kobalts in der Natur. Ztschr. f. Angew. Chem. 19: 1793–1795.
(102) Krisciunas, J.
1936. Effect of the micro-elements for the yield and quality of sugar beets Zemes Ukis. 19–20.
(103) Legrip.
1841. [no title.] Jour. Chim. Med. Pharma., et Toxicol (2) 7: 120.
(104) Lines, E. W.
1935. Effect of ingestion of minute quantities of cobalt by sheep affected with "coast disease." Austral. Council Sci. & Indus. Res. Jour. 8: 117–119, illus.
(105) Lundegardh, H., and Burström, H.
1935. Untersuchungen über die Atmungsvorgänge in Pflanzenwurzeln. Biochem. Ztschr. 277: 223–249, illus.
(106) Lundegardh, P. H.
1945. Distribution of vanadium, chromium, cobalt, and nickel in eruptive rocks. Nature (London) 155: 753.
(107) Lundegardh, Per H.
1946. Geochemistry of magmatic iron ore. Nature [London] 157: 625–626.
(108) Lyford, W. H., Jr., Percival, G. P., Keener, H. A., and Morrow, K. S.
1946. The soils of New Hampshire as related to a deficiency in cattle responding to cobalt. Soil Sci. Soc. Amer. Proc. 10: 375–380, illus.
(109) McDonald, Ian W.
1942. The occurrence of uncomplicated cobalt deficiency of sheep in South Australia. Austral. Vet. Jour. 18: 107–115, illus.
(110) McHargue, J. S.
1925. The occurrence of copper, manganese, zinc, nickel, and cobalt in soils, plants, and animals, and their possible function as vital factors. Jour. Agr. Res. 30: 193–196.
(111) ———
1927. Significance of the occurrence of manganese, copper, zinc, nickel, and cobalt in Kentucky bluegrass. Jour. Indus. and Engin. Chem. 19: 274–276, illus.
(112) McNaught, K. J.
1937. Cobalt content of limonites used in the treatment of bush sickness. New Zeal. Jour. Sci. and Technol. 18: 655–661, illus.

(113) ———
1938. COBALT CONTENT OF NORTH ISLAND PASTURES. New Zeal. Jour. Sci. and Technol. 20A: 14–30.

(114) ———
1938. COBALT CONTENT OF BOTH PASTURES. New Zeal. Jour. Agr. 57: 209–210, illus.

(115) ———
1938. COBALT CONTENT OF THE AROHENA PASTURES. New Zeal. Jour. Agr. 57: 212.

(116) ——— and PAULL, G. W.
1939. SEASONAL VARIATION IN COBALT CONTENT OF NORTH ISLAND PASTURES. New Zeal. Jour. Sci. and Technol. 21B: 95–101.

(117) ——— and PAULL, G. W.
1940. A CASE OF COBALT DEFICIENCY ON LIMESTONE SOIL. New Zeal. Jour. Sci. and Technol. 21A: 343–344.

(118) MAIER, WILLI.
1937. BORMANGELERSCHEINUNGEN AN REBSÄMLINGEN IN WASSERKULTURVERSUCHEN. Gartenbauwissenschaft 11: 1–16, illus.

(119) MARSTON, H. R.
1935. PROBLEMS ASSOCIATED WITH "COAST DISEASE" IN SOUTH AUSTRALIA. Austral. Council Sci. & Indus. Res., Jour. 8: 111–116.

(120) ——— THOMAS, R. G., LINES, E. W. L., MCDONALD, I. W., MOORE, H. O., and BULL, L. B.
1938. STUDIES ON "COAST DISEASE" OF SHEEP IN SOUTH AUSTRALIA. Austral. Council Sci. & Indus. Res., Bul. 113: 91 pp., illus.

(121) MAUNSELL, PATRICIA W.
1945. RATE OF GROWTH AND COBALT CONTENT OF PASTURE. New Zeal. Jour. Sci. and Technol. 27A: 40–41.

(122) ———
1945. THE COBALT CONTENT OF SOME NORTH ISLAND (NEW ZEALAND) LIMESTONES. New Zeal. Jour. Sci. and Technol. 27A: 42–44.

(123) ——— and SIMPSON, J. E. V.
1944. INVESTIGATION TO DETERMINE SUITABLE METHODS OF APPLYING COBALT SULPHATE TO PASTURES DURING FERTILIZER SHORTAGE. New Zeal. Jour. Sci. and Technol. 26A: 142–145.

(124) MILLIKAN, C. R.
1947. EFFECT OF MOLYBDENUM ON THE SEVERITY OF TOXICITY SYMPTOMS IN FLAX INDUCED BY AN EXCESS OF EITHER MANGANESE, ZINC, COPPER, NICKEL OR COBALT IN THE NUTRIENT SOLUTION. Austral. Inst. Agr. Sci. Jour. 13: 180–186.

(125) MITCHELL, R. L.
1944. DISTRIBUTION OF TRACE ELEMENTS IN SOIL AND GRASSES. Nutr. Soc. (Engl. and Scotl.) Proc. 1 (3–4): 183–189.

(126) ———
1945. COBALT AND NICKEL IN SOILS AND PLANTS. Soil Sci. 60: 63–70.

(127) ———
1946. APPLICATIONS OF SPECTROGRAPHIC ANALYSIS TO SOIL INVESTIGATIONS. Analyst 71: 361–368, illus.

128) ——— SCOTT, R. O., STEWART, A. B., and STEWART, JAMES.
1941. COBALT MANURING AND PINING IN STOCK. Nature [London] 148: 725–726.

(129) MOKRAGNATZ, M.
1931. ACTION DU NICKEL ET DU COBALT SUR LE DEVELOPMENT DE L'ASPERGILLUS NIGER. Soc. de Chim. Biol. Bul. 13: 61–71.

(130) MORTENSEN, M. L.
1909. VERSUCHE ÜBER DIE GIFTWIRKUNG VON KOBALT-SALZEN AUF ASPERGILLUS NIGER BEI KULTUR AUF FESTEN UND FLÜSSIGEN MEDIEN. Zentrbl. f. Bakt. [etc.] Abt. II, 24: 521–538.

(131) NAKAMURA, M.
1904. CAN SALTS OF ZINC, COBALT, AND NICKEL IN HIGH DILUTION EXERT A STIMULANT ACTION ON AGRICULTURAL PLANTS? Tokyo Imp. Univ. Col. Agr. Bul. 6: 147–152.

(132) NEAL, W. M., and AHMANN, C. F.
1937. THE ESSENTIALITY OF COBALT IN BOVINE NUTRITION. Jour. Dairy Sci. 20: 741–753, illus.

(133) NĚMEC, B., and BABIČKA, J.
1935. CHLOROSIS OF PLANTS PRODUCED BY COBALT. Mem. Soc. Roy. des Sci. Bohême (Věst. Královské České Společnosti Nauk, Třida II, Ročník (1934)) 19, 28 pp.
(134) NIELSEN, NIELS, and HARTELIUS, VAGN.
1935. ÜBER DIE CO-WUCHSSTOFFWIRKUNG EINIGER METALLMISCHUNGEN. Biochem. Ztschr. 276: 183–185.
(135) NOCKOLDS, S. R., and MITCHELL, R. L.
1948. THE GEOCHEMISTRY OF SOME CALEDONIAN PLUTONIC ROCKS: A STUDY IN THE RELATIONSHIP BETWEEN THE MAJOR AND TRACE ELEMENTS OF IGNEOUS ROCKS AND THEIR MINERALS. Roy. Soc. Edinb., Trans. 61: Pt. II, 533–575 (1944–1948).
(136) ONO, N.
1900. UEBER DIE WACHSTHUMSBESCHLEUNIGUNG EINIGER ALGEN UND PILZE DURCH CHEMISCHE REIZE. Tokyo Imp. Univ., Col. Sci. Jour. 13: 141–186, illus.
(137) OERTEL, A. C., PRESCOTT, J. A., and STEPHENS, C. G.
1946. THE INFLUENCE OF SOIL REACTION ON THE AVAILABILITY OF MOLYBDENUM TO SUBTERRANEAN CLOVER. Austral. Jour. Sci. 9: 27–28, illus.
(138) PATTERSON, J. B. E.
1937. COBALT AND SHEEP DISEASES. Nature [London] 140: 363.
(139) ———
1938. SOME OBSERVATIONS ON A DISEASE OF SHEEP ON DARTMOOR. Empire Jour. Expt. Agr. 6: 262–267.
(140) ———
1946. COBALT AS A PREVENTIVE OF "PINING" IN CORNWALL AND DEVON. Nature [London] 157: 555.
(141) PETRI, L.
1910. OBSERVATIONS ON INJURIOUS EFFECTS OF TOXIC SUBSTANCE ON THE OLIVE TREE. Zentbl. f. Bakt. [etc.] Abt. II, 28 (4–5) : 153–159.
(142) PIRSCHLE, KARL.
1930. ZUR PHYSIOLOGISCHEN WIRKUNG HOMOLOGER IONENREIHEN. Jahrb. f. Wiss. Bot. 62: 335–368, illus.
(143) PEREIRA, FORJAZ.
1931. LA BIOCHEMIE DE LA NITRIFICATION (NOUVELLE CONTRIBUTION À L'ÉTUDE DU PROCÉDÉ MUNTZ). Chim. & Indus. [Paris] 25 (3; Spec. No.) : 829.
(144) PURVIS, E. R., and RUPRECHT, R. W.
1935. SOIL AND FERTILIZER STUDIES WITH CELERY. Fla. Agr. Expt. Sta. Ann. Rpt. 1935: 63.
(145) ——— and RUPRECHT, R. W.
1936. SOIL AND FERTILIZER STUDIES WITH CELERY. Fla. Agr. Expt. Sta. Ann. Rpt. 1936: 61.
(146) RAMAGE, HUGH.
1936. BIOLOGICAL DISTRIBUTION OF METALS. Nature [London] 137: 67.
(147) RICEMAN, D. S., and DONALD, C. M.
1938. PRELIMINARY INVESTIGATIONS ON THE EFFECT OF COPPER AND OTHER ELEMENTS ON THE GROWTH OF PLANTS IN A "COASTY" CALCAREOUS SAND AT ROBE, SOUTH AUSTRALIA. Austral. Council Sci. & Indus. Res., Pam. 78: 1–23, illus.
(148) ——— DONALD, C. M., and PIPER, C. S.
1938. RESPONSE TO COPPER ON A SOUTH AUSTRALIAN SOIL. Austral. Inst. Agr. Sci. Jour. 4: 41.
(149) RICHARDS, HERBERT MAULE.
1897. DIE BEEINFLUSSUNG DES WACHSTHUMS EINIGER PILZE DURCH CHEMISCHES REIZE. Jahrb. F. Wiss. Bot. 30: 665–688.
(150) [RIGG, T.]
1939. MINERAL CONTENT OF PASTURES. New Zeal. Dept. Sci. and Indus. Res. Ann. Rpt. 13: 10.
(151) ———
1940. MINERAL CONTENT OF PASTURES. COBALT INVESTIGATIONS AT THE CAWTHRON INSTITUTE, 1939–40. New Zeal. Dept. Sci. and Indus. Res. Ann. Rpt. 14: 41–44.

(152) ——— and Askew, H. O.
1934. SOIL AND MINERAL SUPPLEMENTS IN THE TREATMENT OF BUSH SICKNESS. Empire Jour. Expt. Agr. 2: 1–8, illus.

(153) ——— and Askew, H. O.
1936. FURTHER INVESTIGATIONS ON BUSH-SICKNESS AT GLENHOPE, NELSON, NEW ZEALAND. Empire Jour. Expt. Agr. 4: 1–5, illus.

(154) Ritchie, G. B.
1946. THE EFFECT OF COPPER AND COBALT DEFICIENCY ON SHEEP AND WOOL. So. Austral. Dept. Agr. Jour. 50: 163–165.

(155) Robinson, W. O.
1914. THE INORGANIC COMPOSITION OF SOME IMPORTANT AMERICAN SOILS. U. S. Dept. Agr. Bul. 122, 27 pp.

(156) ———
1945. GREEN COLOR OF PLANT ASH DUE TO MANGANESE, NOT TO COBALT. Science 102: 158.

(157) Rossiter, R. C., Curnow, D. H., and Underwood, E. J.
1948. THE EFFECT OF COBALT SULPHATE ON THE COBALT CONTENT OF SUBTERRANEAN CLOVER (TRIFOLIUM SUBTERRANEUM L. VAR. DWALGANUP) AT THREE STAGES OF GROWTH. Austral. Inst. Agr. Sci. Jour. 14: 9–14.

(158) Roxas, Manuel.
1911. THE EFFECT OF SOME STIMULANTS UPON RICE. Philippine Agr. and Forester 1: 89–97.

(159) Russell, F. C.
1944. MINERALS IN PASTURE. DEFICIENCIES AND EXCESSES IN RELATION TO ANIMAL HEALTH. Imp. Bur. Anim. Nutr., Tech. Commun. 15: 91.

(160) Samuel, Geoffrey, and Piper, C. S.
1929. MANGANESE AS AN ESSENTIAL ELEMENT FOR PLANT GROWTH. Ann. Appl. Biol. 16: 493–524, illus.

(161) Sandell, Ernest B., and Goldich, Samuel S.
1943. THE RARER METALLIC CONSTITUENTS OF SOME AMERICAN IGNEOUS ROCKS. Jour. Geol. 51: 99–115, 167–189.

(162) Scharrer, K., and Schropp, W.
1933. SAND- UND WASSERKULTURVERSUCHE MIT NICKEL UND KOBALT. Ztschr. f. Pflanzenernähr., Düngung u. Bodenk. 31A: 94–113, illus.

(163) Schropp, W., and Scharrer, K.
1933. WASSERKULTURVERSUCHE MIT DER "A-Z LOSUNG" NACH HOAGLAND. Jahrb. f. Wiss. Bot. 78: 544–563.

(164) Sempio, C.
1935. INFLUENZA DEL CO E DI ALTRI CATIONI SULLE SVILUPPO DI TUMORI SPERIMENTALI DA BACTERIUM TUMEFACIENS SU PIANTINE DI RICION. Soc. Ital. per il Prog. delle Sci. Atti 23 (III): 147–150.

(165) Singh, B. H., and Prasad, S.
1936. THE TOLERANCE OF WHEAT PLANTS FOR CHLORIDES OF CERTAIN NONESSENTIAL ELEMENTS. Indian Jour. Agr. Sci. 6: 720–724, illus.

(166) Slater, C. S., Holmes, R. S., and Byers, H. G.
1937. TRACE ELEMENTS IN THE SOILS FROM THE EROSION EXPERIMENT STATIONS, WITH SUPPLEMENTARY DATA ON OTHER SOILS. U. S. Dept. Agr. Tech. Bul. 552, 23 pp.

(167) Smith, Henry G.
1903. ALUMINUM THE CHIEF ORGANIC ELEMENT IN A PROTEACEOUS TREE, AND THE OCCURRENCE OF ALUMINUM SUCCINATE IN TREES OF THIS SPECIES. Chem. News 88: 135–136.

(168) Somers, I. I., and Shive, T. W.
1942. THE IRON-MANGANESE RELATION IN PLANT METABOLISM. Plant Physiol. 17: 582–602, illus.

(169) Spencer, Ernest L.
1937. FRENCHING OF TOBACCO AND THALLIUM TOXICITY. Amer. Jour. Bot. 24: 16–24, illus.

(170) Stanton, D. J.
1944. THE COBALT CONTENT OF SOME SOUTH ISLAND (NEW ZEALAND) LIMESTONES. New Zeal. Jour. Sci. and Technol. 25A: 221–224.

(171) ——— and Kidson, E. B.
1939. COBALT STATUS OF SOILS AND PASTURES IN THE SHERRY AND WANGAPEKA DISTRICTS, NELSON. New Zeal. Jour. Sci. and Technol. 21B: 67–76, illus.

(172) Steinberg, R. A.
1920. EFFECT OF ZINC AND IRON COMPARED WITH THAT OF URANIUM AND COBALT ON GROWTH OF ASPERGILLUS. Bot. Gaz. 70: 465–468.

(173) Stewart, James, Mitchell, R. L., and Stewart, A. B.
1941. PINING IN SHEEP: ITS CONTROL BY ADMINISTRATION OF COBALT AND BY USE OF COBALT-RICH FERTILIZERS. Empire Jour. Expt. Agr. 9: 145–152, illus.

(174) ——— Mitchell, R. L., and Stewart, A. B.
1942. PINING IN SHEEP. II. CONFIRMATORY EXPERIMENTS ON ITS CONTROL BY COBALT-RICH FERTILIZERS. Empire Jour. Expt. Agr. 10: 57–60.

(175) ——— Mitchell, R. L., Stewart, A. B., and Young, H. M.
1946. SOLWAY PINE: A MARASMIC CONDITION IN LAMBS IN CERTAIN DISTRICTS OF KIRKCUDBRIGHTSHIRE. Empire Jour. Expt. Agr. 14: 145–152, illus.

(176) Thomas, R. G.
1938. STUDIES ON "COAST DISEASE" OF SHEEP IN SOUTH AUSTRALIA. IV. THE INFLUENCE OF GEOLOGICAL CONDITIONS AND SOIL COMPOSITION ON REGIONAL DISTRIBUTION OF "COAST DISEASE" IN SHEEP IN SOUTH AUSTRALIA. Austral. Council Sci. & Indus. Res., Bul. 113: 28–39, illus.

(177) ———
1940. SOME GEOCHEMICAL ASPECTS OF ANIMAL ECOLOGY. Austral. Jour. Sci. 3: 33–40, 53–59.

(178) Thompson, John F., and Ellis, Gordon H.
1947. IS COBALT A DIETARY ESSENTIAL FOR THE RABBIT? Jour. Nutr. 34: 121–127.

(179) Tröger, E.
1935. DER GEHALT AN SELTENEREN ELEMENTEN BEI ERUPTIVGESTEINEN. Chem. der Erde 9: 286–310.

(180) Underwood, E. J., and Elvehjem, C. A.
1938. IS COBALT OF ANY SIGNIFICANCE IN THE TREATMENT OF MILK ANEMIA WITH IRON AND COPPER? Jour. Biol. Chem. 124: 419–424.

(181) ——— and Filmer, J. F.
1935. THE DETERMINATION OF THE BIOLOGICALLY POTENT ELEMENT (COBALT) IN LIMONITE. Austral. Vet. Jour. 11: 84–92, illus.

(182) ——— and Harvey, R. J.
1938. ENZOOTIC MARASMUS: THE COBALT CONTENT OF SOILS, PASTURES, AND ANIMAL ORGANS. Austral. Vet. Jour. 14: 183–189.

(183) Vernadsky, W. J.
1922. SUR LE NICKEL ET LE COBALT DANS LA BIOSPHERE. [Paris] Acad. des Sci. Compt. Rend. 175: 382–385.

(184) Wager, L. R., and Mitchell, R. L.
1943. PRELIMINARY OBSERVATIONS ON THE DISTRIBUTION OF TRACE ELEMENTS IN THE ROCKS OF THE SKAERGAARD INTRUSION, GREENLAND. Min. Mag. 26: 283–296.

(185) ——— and Mitchell, R. L.
1945. DISTRIBUTION OF VANADIUM, CHROMIUM, COBALT, AND NICKEL IN ERUPTIVE ROCKS. Nature [London] 156: 207–208.

(186) Wall, Eunice M.
1937. TRACE ELEMENTS IN RELATION TO BUSH SICKNESS. New Zeal. Jour. Sci. and Technol. 18: 642–650, illus.

(187) Walrath, E. K., Ward, R. E., and Struve, O. I.
1948. YIELD AND COMPOSITION OF FORAGE GROWN ON ONE CONNECTICUT FARM IN 1946. Soil Sci. 65: 259–273.

(188) Washington, Henry S.
1925. THE CHEMICAL COMPOSITION OF THE EARTH. Amer. Jour. Sci. (V) 9: 351–378.

(189) Watson, Joyce.
1943. THE EFFECT OF DRESSINGS OF COBALT AND LIMESTONE ON THE MOLYBDENUM CONTENT OF SOME SOUTH ISLAND PASTURES. New Zeal. Jour. Sci. and Technol. 25A: 161–164.

(190) WUNSCH, D. S.
1937. TRACKING DOWN A DEFICIENCY DISEASE. Chem. Indus. 1937: 855–859.
(191) ———
1939. TRACE ELEMENTS IN LIVESTOCK DISEASES. Chem. Indus. 1939: 531–533.
(192) YOUNG, R. S.
1935. CERTAIN RARER ELEMENTS IN SOILS AND FERTILIZERS AND THEIR ROLE IN PLANT GROWTH. N. Y. (Cornell) Agr. Expt. Sta. Mem. 174, 70 pp.
(193) ZEHL, BERNHARD.
1908. DIE BEEINFLUSSUNG DER GIFTWIRKUNG DURCH DIE TEMPERATURE, SOWIE DURCH DAS ZUSAMMENGREIFEN VON ZWEI GIFTEN. Ztschr. f. Allg. Physiol. 8: 140–190.
(194) ZELENOV, V. G.
1940. THE ACTION OF FERTILIZERS CONTAINING COPPER ON PEAT SOILS. [Moscow] Trudy TSKLA 5 (1): 251–259.
(195) ZEPPELIN, H. v., and GLASS, W.
1938. KOBALT ALS HEILMITTEL BEI WEIDEKRANKHEITEN. Ernähr. der Pflanze 34: 186–189, illus.

U. S. GOVERNMENT PRINTING OFFICE: 1950

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price 15 cents